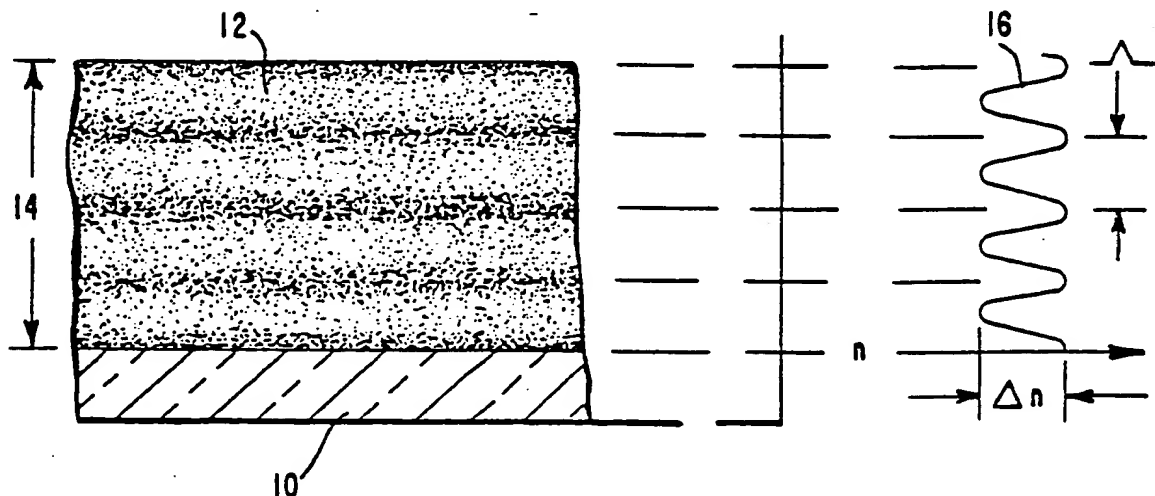




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(54) Title: GRADED INDEX ASPHERIC COMBINERS AND DISPLAY SYSTEM UTILIZING SAME



## (57) Abstract

An improved optical combiner useful in many applications. The combiner includes a substrate (10) with at least one aspheric surface and a diffraction-type reflective coating (12) formed on the substrate (10) for selectively reflecting radiation within one or more predetermined narrow band ranges of wavelengths impinging on the coating. The asphericity of the surface may be selected to compensate or balance optical aberrations. The coating is advantageously a graded-index (16) coating (12), which eliminates the possible degradation of gelatin hologram coatings due to moisture. A process for applying the graded-index (16) coating (12) to a substrate (10) is disclosed. The variation in the index profile of the coating can be selected to provide the capability of combiners with multiple color reflectivity responses, or which allow use of display light sources of wider spectral bandwidth, resulting in a brighter image and improved angular bandwidth.

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GRADED INDEX ASPHERIC COMBINERS  
AND DISPLAY SYSTEM UTILIZING SAME

1           This application is a continuation-in-part of  
application serial number 528,833, filed September 2,  
1983, entitled "Process for Forming a Graded Index  
Optical Material and Structures Formed Thereby," and  
5           application serial number 600,636, filed April 16,  
1984, entitled "Biocular Holographic Helmet Mounted  
Display," each application assigned to the same assignee  
as this application.

10                           BACKGROUND OF THE INVENTION

          This invention relates generally to reflective  
optical materials, and more particularly to reflective  
diffraction and interference-type optical elements,  
such as optical filters and combiners, which are used,  
15          for example, in head-up displays or helmet-mounted  
visor displays.

1           In various optical systems, it is often necessary  
to provide a filter in order to remove undesired  
radiation while at the same time allowing desired  
radiation to be efficiently transmitted or reflected.  
5   Such filters and coatings are used, for example, to  
provide protection from laser radiation for personnel,  
for electro-optical detectors, and for optical mirrors  
in a laser system, as a holographic lens in a head-up  
display system, or in night vision devices. The optical  
10 filters currently used for such purposes include absorp-  
tion filters, reflective multiple layer dielectric  
filters, and diffraction filters generated by optical  
holographic techniques. However, each of these approaches  
to providing optical filters has certain disadvantages,  
15 as discussed below.

          The absorption filter comprises a material which  
is impregnated with absorption dyes or materials with  
intrinsic absorption at the wavelength of the incoming  
laser radiation, as described, for example, in the book  
20 entitled "Handbook of Optics", W. G. Driscoll, ed.,  
McGraw-Hill Book Co., New York, 1978, in Section 8  
(Coatings and Filters), at pages 7 to 32. This type  
of protection has the serious disadvantage that the  
absorbing dye decreases the amount of transmitted  
25 radiation to unacceptably low levels. In addition,  
for laser applications, as the laser radiation energy  
increases, the radiation can damage the protective  
filter itself.

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1           The reflective multiple layer dielectric filters  
typically consist of alternate layers of two dielectric  
materials of different refractive indices, which are  
formed on the surface of a substrate by known deposition  
5 techniques, such as chemical vapor deposition, sputtering,  
or thermal evaporation. When the optical thickness of  
each layer is chosen to be one-quarter of the wavelength  
of the radiation being reflected, such a structure is  
referred to as a "quarterwave stack", as discussed, for  
10 example, in U.S. Patent No. 4,309,075 and in the book  
entitled "Handbook of Optics", previously referenced,  
in particular in Section 8. However, there are limita-  
tions on the spectral bandwidths which can be achieved  
by such structures, because of the limited material  
15 combinations available and the resulting restriction on  
the choices of index modulations. Moreover, defects at  
the abrupt interfaces between the layers in a multilayer  
structure can cause unwanted optical scattering. In  
addition, these defects can cause excessive absorption  
20 of radiation by the dielectric material, which can  
result in thermal damage to the optical filter.  
Furthermore, in a multilayer dielectric coating, the  
electric field is strongest at the interface regions  
between the high index material and the low index  
25 material. This highly localized field occurring at the  
abrupt interfaces can produce maximum temperature  
increases. Since the thermal expansion coefficients  
are different for the different dielectric materials of  
adjacent layers, high thermal stress is developed at  
30 the interface regions, which could cause delamination  
of the successive layers in the film. In addition,  
the high thermal stress could create microscopic

1 dislocations which result in unwanted optical scattering  
by the film. Further, substrate roughness, pinholes  
and contaminants in the conventional multilayer  
structures formed by evaporation or sputtering  
5 techniques increase absorption and scattering, generate  
localized heating, reduce maximum reflectivity, and  
increase radiation damage. Finally, these multilayer  
coatings exhibit reflectance peaks at multiple wave-  
lengths, which causes reduced optical transmission.

10 Diffraction optical elements have been generated  
using known methods of optical holography in photo-  
sensitive gelatin material, as discussed, for example,  
in the book entitled "Optical Holography", by Collier,  
Burckhardt, and Lin, Academic Press, New York, 1971,  
15 Chapter 9 (Diffraction from Volume Holograms) and  
Chapter 10 (Hologram Recording Materials), as well as  
in the book entitled "Handbook of Optical Holography",  
by Caulfield, Academic Press, New York, 1979, Chapter. 10  
(Application Areas). However, gelatin diffraction  
20 elements have environmental stability problems and are  
susceptible to degradation by humidity and heat. In  
order to overcome this problem, a protective layer such  
as glass or a glass-like coating can be used, but  
such a layer complicates the manufacturing process and  
25 adds to unit cost. Moreover, such gelatin filters are  
limited to use for radiation in the wavelength range  
from the visible to the near infrared (i.e., up to about  
2 microns) since sensitized gelatin is not sensitive  
to longer wavelength exposures. Consequently, filters  
30 for infrared applications cannot be fabricated in a  
gelatin structure. In addition, the index modulation  
in the gelatin, which is produced by exposure to the  
holographic interference pattern and subsequent develop-  
ment, is limited to a shape approximating a sinusoidal

1 configuration or a roughly superimposed multiple  
sinusoidal configuration. Furthermore, the fabrication  
of a gelatin filter requires numerous steps, in particular  
numerous wet chemical steps for development, which are  
5 sensitive to processing variables, such as temperature  
or vibration, that affect the efficiency and peak  
wavelength of the final structure. In addition, since  
the resistance of gelatin to damage by heat or radiation  
is relatively low, gelatin filters are limited to low  
10 power applications. Finally, fabrication of a filter  
which reflects radiation at two selected wavelengths  
requires multiple exposure of the gelatin to two  
holographic patterns, which produces an irregular  
index profile that reduces the efficiency of the filter.

15 One general application in which gelatin filters  
have heretofore been employed is that of the optical  
combiner element of a reflective display, such as a  
head-up display (HUD) or helmet visor display (HVD)  
commonly used in aircraft display systems. U.S. Patent  
20 3,940,204 discloses exemplary HUD and HVD systems. The  
laminated gelatin holographic combiner employed for  
these applications typically comprises a spherical  
plastic substrate to which are bonded successive layers of  
glass, the gelatin hologram, glass, plastic and an  
25 antireflective (AR) coating. The glass layers sandwiching  
the gelatin are required to protect the gelatin from  
degradation by humidity. As a result of the multiple  
layers, strong undesirable ghost images may be produced  
by the gelatin holographic combiners.

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1           Combiners for display systems can be designed to  
compensate or balance aberrations in the display system.  
The compensation may comprise the implementation of  
aspheric reflective layers or surfaces. With the  
5       state of the current technology it is not economically  
feasible, on a production basis, to provide glass layers  
or substrates with aspheric surfaces. Instead the  
required asphericity is incorporated into the gelatin  
hologram itself, which means that the fringes will be  
10       slanted varying degrees with respect to the gelatin  
surfaces. This creates a grating at the hologram  
surface and results in a phenomenon known as chromatic  
dispersion, wherein the direction of light diffracted from  
the hologram is wavelength dependent. In a holographic  
15       display such as the HUD or HVD, if the display light  
source has any appreciable spectral bandwidth, chromatic  
dispersion will blur the image at the exit pupil,  
perhaps to an unacceptable level. Even with narrow band  
light sources, such as a cathode ray tube (CRT) with  
20       P43 phosphor, the fringe slant in some areas of the  
hologram may be large enough to cause significant  
dispersion-induced degradation of the image. Slant  
fringes may also result in flare, a condition in which  
extraneous diffraction images are produced. The  
25       extraneous diffraction may obscure the field of view.

A gelatin holographic combiner for a HUD or visor  
display is relatively complex and expensive to fabricate.  
For example, a typical gelatin holographic visor having  
impact resistance consists of a multi-layer laminant in  
30       which the gelatin hologram is sandwiched between two  
pieces of glass for humidity protection and then



1 laminated between two pieces of polycarbonate visor for  
impact requirements. Antireflective coatings are  
applied to the respective outer surfaces of the  
polycarbonate pieces. The multiple laminate adds  
5 weight and complexity to the system. The gelatin  
holographic HUD combiner is similarly complex and heavy.

The weight of the combiner is an important  
consideration in the weight-critical cockpit environment.  
As a result of the relatively high weight of the visor  
10 gelatin hologram combiner in an HVD, the visor display  
center of mass is moved away from the pivot point of  
the pilot's head, so that the burden on his neck is  
increased. The increased cantilevered mass in the HUD  
gelatin hologram combiner decreases the combiner  
15 stiffness and resistance to vibration.

#### SUMMARY OF THE INVENTION

The present invention provides an improved optical  
combiner which is useful in many applications, including  
20 HVD and HUD applications. The combiner comprises a  
substrate having at least one aspheric surface and a  
diffraction-type reflective coating formed on this  
surface for selectively reflecting radiation within one  
or more predetermined narrow band ranges of wavelengths  
25 impinging on the coating. The asphericity of the  
surface may be selected to compensate or balance optical  
aberrations in the display system. The coating may  
comprise a gelatin hologram, but preferably is a graded-  
index coating which eliminates the potential degradation of  
30 gelatin holograms by a humid environment and eliminates  
the significant difficulties encountered in attempting  
to apply an even gelatin coating to an aspheric surface.

1 The variation in the index of refraction may occur  
throughout the thickness of the coating and across the  
horizontal and lateral extent of the coating as well.  
A non-sinusoidal variation in the index profile throughout  
5 the thickness of the coating can produce a broadened  
peak in the spectral reflectivity function, as well as  
multiple peaks. This feature provides the capability  
of combiners with multiple color reflectivity responses,  
or which allow use of display light sources of wider  
10 spectral bandwidth, resulting in a brighter image and  
improved angular bandwidth.

In one embodiment the combiner is incorporated in  
a biocular helmet visor display resulting in improved  
optical performance, significant weight savings and a  
15 simpler, lower cost combiner structure. In another  
embodiment the combiner is incorporated into a head-up  
display for an aircraft resulting in improved optical  
performance, lower weight, improved safety and greater  
look-up capability.

20 Accordingly, it is a further purpose of the  
present invention to provide a new and improved optical  
combiner which substantially eliminates the chromatic  
dispersion and flare characteristics of slanted-fringe  
hologram combiners.

25 Another purpose is to provide an optical combiner  
comprising a substrate having an aspheric surface  
contour to compensate or balance optical aberrations.

Another purpose is to provide an improved optical  
combiner in which the diffraction coating is formed  
30 directly on a substrate and does not require glass  
protective layers.

Yet another purpose is to provide an optical  
combiner which minimizes strong second images.

1 Additional purposes of the invention are to  
provide an optical combiner having a relatively simple,  
lightweight structure which is suitable for fabrication  
by relatively low-cost techniques and with improved  
5 optical tolerances.

Further purposes are to provide improved helmet  
visor displays and head-up displays employing the  
improved optical combiner.

10 The foregoing and other advantages and features of  
the present invention will become more readily apparent  
from the following more particular description of the  
preferred embodiments of the invention, as illustrated in  
the accompanying drawings.

15 BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 presents a graph showing the change in the  
refractive index of a  $\text{SiO}_x$  film which was deposited by  
a photochemical vapor deposition process, as a function of  
the flow rate of the silane reactant.

20 FIG. 2 is a schematic representation of the con-  
tinuously graded index material in a sinusoidal pattern,  
formed in accordance with the present invention.

FIG. 3 presents a graph showing the dependence of  
the thickness of the deposited oxide on the relative  
25 intensity of the ultraviolet light used to initiate the  
photochemical vapor deposition reaction of one embodiment  
of the present invention.

FIG. 4 is a schematic diagram of a structure having  
an aspheric substrate surface and a diffraction optical  
30 element formed on the surface thereof in accordance with  
the present invention.

1           FIG. 5 shows a curve indicating the measured spectral reflectance of a filter formed in accordance with the present invention, while FIG. 6 presents the theoretical reflectance for such a structure.

5           FIG. 7 presents the refractive index profile for a composite index filter formed in accordance with the present invention which reflects three separate wavelengths of radiation, while FIG. 8 presents the spectral response for such a composite index filter.

10          FIG. 9 is a schematic diagram of an optical combiner having an aspheric substrate structure and a diffraction coating formed on the surface thereof.

          FIG. 10 shows curves of the spectral reflectivity function of a typical gelatin hologram (broken line) with a sinusoidal index profile and a graded-index coating (solid line) with a non-sinusoidal index profile.

15           FIG. 11 shows curves of the spectral reflectivity function of typical gelatin holograms with sinusoidal index profiles (broken line), one designed to have a broad spectral bandwidth relative to the other, and a graded-index coating with a non-sinusoidal index profile (solid line) designed to have a broad spectral bandwidth.

20           FIG. 12 is a schematic representation of a combiner structure comprising a graded-index coating in which the periodicity (and therefore the peak efficiency wavelength) of the index profile function varies as a function of the surface position coordinates.

25           FIGS. 13 and 14 depict structures used in a preferred method to fabricate a plastic combiner substrate having an aspheric surface.

30           FIG. 15 is a simplified schematic drawing of a helmet visor display system incorporating a novel optical combiner in accordance with the invention.

          FIG. 16 is a side view of the HVD system depicted in FIG. 15.

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1           FIG. 17 is an angled side view of the HVD system depicted in FIG. 15, from a plane parallel to a reference line of the system.

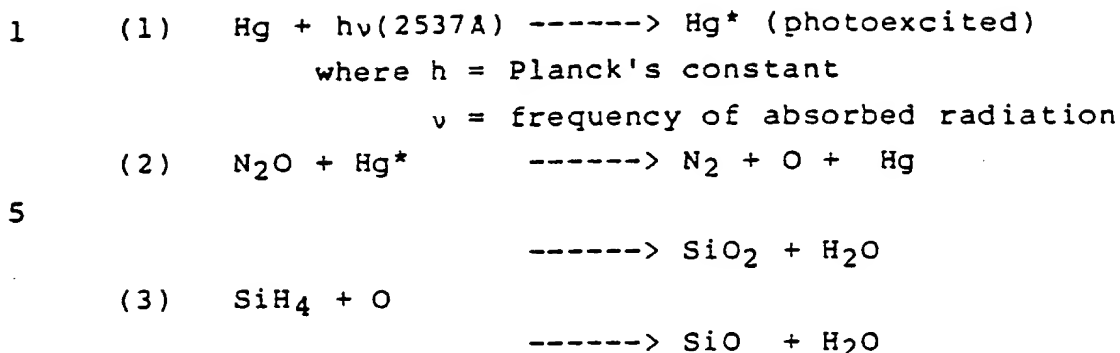
5           FIG. 18 is another side view of the HVD system depicted in FIG. 15, illustrating the diffraction of image source light rays.

          FIG. 19 is a perspective view of the HVD of FIG. 15 shown mounted on a helmet.

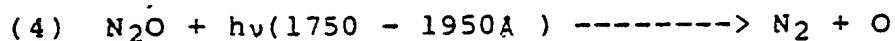
10          FIG. 20 is a simplified schematic view of a head-up display incorporating a novel optical combiner in accordance with the invention.

#### DETAILED DESCRIPTION OF THE INVENTION

15          In order to form the continuously graded index optical material of the present invention, it is required that the process for forming such a material be capable of a high degree of control over the composition of the deposited material. For the deposition of a continuously graded index oxide material, a particularly useful  
20          process is the low temperature, charge-free photochemical vapor deposition process described in U.S. Patent No. 4,371,587, assigned to the present assignee, and the details of which are incorporated herein by reference. In one embodiment of the latter invention, neutral,  
25          charge-free atomic oxygen is generated by the mercury-sensitized photodissociation of a chosen oxygen-containing precursor, such as nitrous oxide, as shown in Equations (1) and (2) below. Then, the atomic oxygen is reacted with a selected vapor phase reactant,  
30          such as silane, to form the desired oxide, silicon monoxide (SiO) or silicon dioxide (SiO<sub>2</sub>), as shown in Equation (3) below.



10           In an alternative process embodiment disclosed in  
 U.S. Patent No. 4,371,587, the required atomic oxygen  
 may be generated by the direct photodissociation of a  
 chosen oxygen-containing precursor, such as nitrous  
 oxide ( $\text{N}_2\text{O}$ ), as shown in Equation (4) below. The  
 15   atomic oxygen so formed reacts with the chosen vapor  
 phase reactant as shown in Equation (3) above.



20           The composition of the oxide product of Equation  
 (3) above depends, in part, on the steady state concen-  
 tration of atomic oxygen, which, in turn, depends on the  
 amount of nitrous oxide present for a given amount of  
 silane. Thus, by varying the ratio of the silane and  
 25   nitrous oxide reactants present at a given point in  
 time, the composition of the silicon oxide ( $\text{SiO}_x$ )  
 product can be controlled, to produce a corresponding  
 control of the refractive index of the oxide material  
 deposited. The composition of the  $\text{SiO}_x$  can range  
 30   from  $\text{SiO}$  with a refractive index of 1.9 to  $\text{SiO}_2$  with  
 a refractive index 1.45.

1           The composition of the oxide, as well as the rate  
of deposition, depends on the mass flow of each of the  
reactants, the pump throughput, and the intensity of  
the reaction-inducing radiation. For a constant value  
5       for pump throughput and radiation intensity, the effect  
of changes in the flow rate of one of the reactant  
gases can be determined. FIG. 1 presents a graph  
showing the change in the refractive index of a  $\text{SiO}_x$   
film which was deposited as described above, as a  
10       function of the flow rate of the silane reactant for a  
constant flow rate of  $\text{N}_2\text{O}$  at 62.0 standard cubic  
centimeters per minute (sccm). As can be seen in  
FIG. 1, the refractive index and composition of  
the  $\text{SiO}_x$  film have a well-defined dependence on the  
15       gas flow rate ratio of the reactants. As shown in  
FIG. 1, the index of the  $\text{SiO}_x$  film was varied from  
1.46 to 1.60 by varying the  $\text{SiH}_4$  flow rate by as much  
as a factor of five, while keeping a fixed  $\text{N}_2\text{O}$  flow  
rate. The large variation in flow rate required to  
20       achieve a change in refractive index ( $\Delta n$ ) of 0.14  
indicates that the index can be changed precisely and  
reproducibly by the above-described process.

Consequently, in accordance with the process of  
the present invention, by accurately controlling the  
25       gas flow rate ratio of the silane reactant to the  
nitrous oxide reactant as a function of time, the  
composition of the  $\text{SiO}_x$  product can be controllably  
and continuously altered as a function of time of  
deposition or thickness of the deposited material.

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1 In particular, the gas flow rate of the silane can  
be varied in a sinusoidal pattern to produce a corre-  
sponding sinusoidal variation in the composition of the  
SiO<sub>x</sub> deposited as a function of distance above the  
5 surface of the substrate, as shown in FIG. 2. The  
substrate 10, shown in FIG. 2 has a layer 12 of a  
continuously graded optical material, such as SiO<sub>x</sub>,  
formed on the surface thereof by the above-described  
process. The composition of the SiO<sub>x</sub> material at a  
10 particular point along the depth or thickness 14 of the  
film 12 depends on the particular ratio of the reactant  
gases and the gas flow rate of silane at the time that  
particular material was deposited. Since the gas flow  
rate of the silane is varied in a sinusoidal pattern,  
15 the composition of the SiO<sub>x</sub> material in the layer 14  
will vary in approximately the same sinusoidal pattern,  
taking into account small deviations from linearity.  
Further, since the refractive index of the SiO<sub>x</sub> material  
varies as the composition thereof, it follows that the  
20 refractive index (n) of the SiO<sub>x</sub> material likewise  
varies in a sinusoidal pattern 16 as a function of the  
thickness 14 of the layer 12, as shown in FIG. 2.  
Thus, there is a gradual change in the refractive index  
of the deposited layer 12 between upper and lower  
25 limits of n and in a predetermined pattern. The  
difference between the highest and lowest values of  
the refractive index of the SiO<sub>x</sub> material is  $\Delta n$ , the  
index modulation. The notation  $\Lambda$  in FIG. 2 refers to  
fringe periodicity, the significance of which is  
30 discussed below with regard to wavelength of reflected  
light and Equation (5).



1           Furthermore, the gas flow rate of the silane may  
be varied in some other pattern besides a sinusoidal  
pattern, such as a quasi-sinusoidal, triangular, sawtooth,  
squarewave, or predetermined irregular pattern, to  
5       produce corresponding variations in the composition  
and refractive index of the deposited material.

          In addition to the effect of the reactant gas flow  
rate ratio discussed above, it should also be noted that  
the intensity of the reaction-inducing ultraviolet  
10       radiation affects the rate of deposition of the oxide.  
FIG. 3 presents a graph showing the dependence of the  
thickness of the deposited oxide in a twenty-minute  
period on the relative intensity of the ultraviolet  
(UV) light used to initiate the photochemical reaction.  
15       As shown in FIG. 3, as the intensity of the UV light  
is increased, the thickness of the oxide deposited in a  
given time period or the deposition rate increases.  
The source of the UV light used to generate the data of  
FIG. 3 in accordance with the first process embodiment  
20       of the present invention was a bank of four mercury  
vapor arc lamps with a major output at a wavelength of  
254 nanometers, at a distance of 2.75 inches (6.99  
centimeters) from the substrate. Alternatively, a  
scanning laser beam may be used as the source of  
25       reaction-inducing radiation in accordance with the  
second process embodiment of the present invention, as  
discussed in further detail herein. In addition to the  
reaction parameters discussed above with regard to  
FIGS. 1 and 3, control of the gas-flow pattern and the  
30       gas pressure inside the deposition chamber is also  
necessary for producing reproducible and uniform oxide  
layers.

1           In accordance with the above-described process of  
the present invention, the modulated index layer is  
formed parallel to the substrate surface, to provide a  
zero-degree (non-slanted fringe) diffraction optical  
5   element. However, the modulated index layer of the  
present invention may alternatively be formed on an  
aspheric substrate which incorporates optical power,  
to provide a diffraction optical element which  
compensates or balances optical aberration while providing  
10   undistorted see-through. Such a structure is shown  
schematically in FIGS. 4a and 4b. In FIG. 4a, there  
is shown a substrate 20 having an arbitrarily-shaped  
aspheric surface and formed, for example, of poly-  
carbonate. On the surface of the substrate 20 and  
15   conforming thereto, there is formed in accordance  
with the process of the present invention a layer 22  
comprising a continuously graded index optical material  
in a predetermined index pattern. As a separate  
element, there is shown in FIG. 4a a cover member 24,  
20   in which the surface 26 that faces the substrate 20  
matches the surface profile of the substrate 20. The  
cover member 24 is laminated by means of epoxy or other  
optically transparent adhesive (not shown) to the  
substrate 20 having the layer 22 formed thereon, to  
25   provide the structure shown in FIG. 4b. As represented  
schematically in FIG. 4b, incident radiation 28 of a  
wavelength in the selected reflective band is reflected  
by the graded index layer 22; while radiation 30 with a  
wavelength outside the selected reflective band passes  
30   through the complete structure. When used in a head-up  
display system such as described in U.S. Patent No.  
3,940,204, assigned to the present assignee, incident  
radiation 28 is the light from a cathode ray tube which

1 is diffracted by the graded index layer 22 to the eye  
of the viewer, and the radiation 32 is light from the  
environment outside the cockpit which is transmitted  
through the complete structure of FIG. 4b to the eye of  
5 the viewer. The ability to use such aspheric substrates  
greatly increases the number of diffraction optics  
applications which may be satisfied by the zero-degree  
diffraction optical element of the present invention.  
A structure such as shown in FIG. 4b is useful for  
10 head-up display diffraction optics combiners, for  
example, as previously discussed.

Further, it is anticipated that a slant fringe  
diffraction optical element may be formed in accordance  
with the present invention by positioning the nozzle  
15 slits of one reactant gas near the substrates. The  
other reactant gas flows uniformly across the entire  
substrate surface; and the slits are separated at a  
distance equal to the fringe spacing on the substrate  
surface. The slant angle is controlled by the related  
20 movement of the substrate and the nozzle slits, as the  
deposition proceeds.

The significance of the above-described process  
for forming a continuously graded index optical material  
in a predetermined pattern is that such a process may  
25 be advantageously used to form a reflective diffraction  
optical element which performs similarly to a conventional  
holographic filter, to diffract the incident light and  
produce a preselected diffraction effect, as described,  
for example, in the book entitled "Optical Holography",  
30 previously referenced, in Chapter 1 (Introduction to  
Basic Concepts).

1           The optical properties of a film consisting of  
discrete, multiple layers are well-described by multi-  
layer matrix theory, as discussed, for example, by  
P. H. Berning in the book entitled "Physics of Thin  
5       Films", edited by G. Hass, Academic Press, New York,  
1963, starting at page 69. This theory may be applied  
to the calculations of the optical properties of a  
graded-index film by approximating the graded film  
as a stack of "N" very thin discrete-index layers.  
10       For "N" of a very large value, this approximation is  
sufficiently accurate for the devices of the present  
invention. Using this approximation and conventional  
multilayer film optical theory, the reflectance,  
transmittance, and absorbance for both s- and p-  
15       polarizations, as well as their averages can be  
calculated, preferably with the aid of a computer  
program, for graded-index films. These calculations  
can be made at any wavelength or angle of incidence for  
any graded-index coating configuration. The electric  
20       field and absorption profile within the coating can  
also be calculated. Such calculations indicate the  
feasibility of fabricating narrow band, high reflectance  
spectral filters by deposition of graded index films.  
This method of analyzing graded-index films is described,  
25       for example, by K. A. Winick, in the Final Scientific  
Report on "Thick Phase Holograms", Environmental Research  
Institute of Michigan, January, 1981.

          Calculations of the optical properties of graded  
index films illustrate that the reflectance character-  
30       istic of the film depends primarily on the Fourier  
composition of the index profile. Thus, for example,  
a holographically exposed diffraction optical element  
with sinusoidal index modulation has the same performance  
at the designed reflection wavelength ( $\lambda_p$ ) as that of  
35       the multilayer square modulation of equal periodicity

1 whose fundamental Fourier component is of equal modula-  
tion amplitude. Consequently, for some diffraction  
optics applications where high reflectance at only a  
single wavelength is desired, the squarewave multilayer  
5 film and the sinusoidally modulated film are equally  
viable alternatives, in terms of optical properties.  
However, because of the disadvantages of the multilayer  
structure previously discussed, the sinusoidal profile  
or some other graded index profile which the process  
10 of the present invention provides, may offer distinct  
advantages over the multilayer squarewave profile.

Furthermore, the graded index film of the present  
invention may be designed to have any peak wavelength  
or wavelengths desired, barring materials limitations,  
15 by designing each sinusoidal component of the index  
profile to have a periodicity  $\Lambda$  described in Equation  
(5) below.

(5)  $\Lambda_i = \lambda_{pi}/2n$   
20 where  
 $\Lambda_i$  = periodicity of the  $i^{th}$  sinusoidal component  
in the index profile  
 $\lambda_{pi}$  =  $i^{th}$  peak wavelength  
n = average index of refraction

25  $SiO_x$  graded index filters are material-limited to a  
peak wavelength from 0.4 to 2.5 micrometers, since  $SiO_x$   
becomes highly absorptive outside this range. However,  
other materials besides  $SiO_x$ , such as aluminum oxide or  
30 zirconium oxide, may be used to form a layer with a  
graded index profile which reflects radiation at higher  
or lower wavelengths. Thus, by the process of the present  
invention, diffraction optical elements may be formed to  
reflect radiation in the ultraviolet, visible and  
35 infrared ranges.

1           In addition, in accordance with an alternative to  
the first process embodiment of the present invention,  
the peak reflection wavelength ( $\lambda_p$ ) may be varied  
across the horizontal surface of the diffraction optical  
5       element by varying the localized reactant gas flow rate  
across the substrate surface as desired or by varying  
the intensity of the reaction-inducing radiation, as  
discussed herein, to produce variations in the thickness,  
refractive index, periodicity, and  $\lambda_p$  of the deposited  
10       material. Such devices with horizontal variations of  
 $\lambda_p$  have been heretofore unattainable.

Moreover, the process of the present invention  
may be used to form layers which exhibit modulation in  
either absorptivity or refractive index or both, since  
15       there is a known relationship between absorptivity and  
refractive index. Absorptivity  $\alpha$  is defined in Equation  
(6) below, and the relationship thereof to refractive  
index is defined in Equation (7) below.

20       (6)            $\alpha = \frac{4\pi k}{\lambda}$

where  $\alpha$  = absorptivity

$k$  = extinction coefficient

$\lambda$  = wavelength of incident radiation

25       (7)            $N = n - ik$

where  $N$  = complex refractive index

$n$  = real refractive index

$k$  = extinction coefficient

30       Thus, in the same way that variations in  $n$ , the real  
refractive index, of a layer of material may be produced  
as previously described herein, so may corresponding  
variations in the extinction coefficient,  $k$ , of a

35

1 layer of material be produced. For example, photo-  
chemically deposited oxides, such as  $\text{SiO}_x$ , have a cutoff  
region (e.g. about 2.5 micrometers for  $\text{SiO}_x$ ) at which  
they become highly absorptive, and the absorptivity is  
5 highly dependent on the stoichiometric composition.  
Thus, by varying the stoichiometric composition of  $\text{SiO}_x$   
in accordance with the present invention, a structure may  
be produced which exhibits modulation of absorptivity as  
well as refractive index. Consequently, the detailed  
10 discussion herein with respect to "refractive index" is  
intended to include the "complex refractive index" des-  
cribed above.

Using the above-described photochemical vapor  
deposition process as further described in Example 1,  
15 an oxide filter was formed with a 16-period,  
sinusoidally modulated refractive index that varied  
between 1.45 and 1.63, producing a peak wavelength at  
1.48 micrometers ( $\mu\text{m}$ ). The spectral reflectance of the  
filter was measured for various wavelengths of  
20 incident radiation using a spectrophotometer and  
known procedures, and the curve obtained is shown  
in FIG. 5. A reflectance of 81.3 percent at the  
fundamental wavelength ( $\lambda_0$ ) of 1.48 micrometers was  
obtained, as shown in FIG. 5. This reflectance value  
25 is to be compared to the theoretical prediction of 94.1  
percent reflectance at 1.48  $\mu\text{m}$  shown in FIG. 6, which  
was based on the theory and calculations previously  
discussed.

The fact that the measured reflectance peak of  
30 81.3 percent in FIG. 5 deviated somewhat from the  
predicted 94.1 percent in FIG. 6 indicates that the  
modulated-index pattern of the deposited film deviated  
somewhat from the intended sinusoidal pattern. This

1 conclusion is supported by the observation of small  
reflectance peaks in FIG. 5 at higher-order harmonics:  
1/2  $\lambda_0$  (0.75  $\mu\text{m}$ ) and 2/3  $\lambda_0$  (1.0  $\mu\text{m}$ ). Each  
reflectance spike corresponds to a particular Fourier  
5 component of the refractive index profile. Therefore,  
a perfect sinusoidally modulated index profile will  
exhibit only one reflectance peak, at the fundamental  
wavelength of  $\lambda_0$ . The fact that the higher-order  
peaks in FIG. 5 are low-amplitude indicates that the  
10 deviation of the film from sinusoidality is relatively  
small. It is anticipated that an accurate sinusoidal  
pattern for the refractive index profile can be achieved  
by using a monitoring and feedback loop control system  
for measuring refractive index and thickness of the  
15 film as deposited. The more accurate the sinusoidally  
modulated index profile, the higher the reflectance  
value at the fundamental wavelength.

In addition, with regard to FIG. 5, the absence of  
a measured reflectance peak at  $\lambda_0/3$  (0.5  $\mu\text{m}$ ), which  
20 is characteristic of a multilayer structure, indicates  
that this coating is not a discrete-layer quarterwave  
stack, and is consistent with the result predicted for  
a sinusoidally modulated film.

The above-described theory and calculations can  
25 be used to determine the feasibility of fabricating  
other narrow band, high reflectance spectral filters by  
the process of the present invention. For example,  
using such calculations, it has been determined that a  
coating design with reflectivity of 99.97 percent at  
30 0.53  $\mu\text{m}$  can be achieved with a sinusoidal index profile  
having a modulation of 0.105 and a thickness of 15  $\mu\text{m}$ .  
It has also been determined that as the film thickness  
increases, the index modulation can be reduced and



1 applied for an increased number of cycles, while still  
maintaining the required reflectivity. Another factor  
for consideration is the reflectance bandwidth. The  
larger the index modulation, the wider the reflectance  
5 bandwidth at a given thickness or at a given efficiency  
level, which causes reduced photopic see-through or  
signal transmission. As another example, it has  
been determined from such calculations that an optical  
coating design with a reflectivity of 99.93 percent at  
10 1.315 micrometers can be achieved with a graded index  
layer of  $\text{SiO}_x$  having a sinusoidal profile, with an  
index modulation of 0.42, a thickness of 8.2 micrometers,  
and a modulation period of 0.396 micrometers.

Furthermore, in accordance with the process of  
15 the present invention, there may be formed a coating  
with a composite index profile which is the linear  
superpositioning of a number of sinusoidal index  
profiles and which exhibits high reflectance at multiple  
wavelengths corresponding to the individual sinusoidal  
20 index profiles. This kind of composite profile can be  
designed analytically as described above and fabricated  
using the graded index process of the present invention.  
For example, the three separate index profiles required  
to provide protection against three separate wavelengths  
25 of radiation at 0.6  $\mu\text{m}$ , 0.8  $\mu\text{m}$ , and 1.0  $\mu\text{m}$  are combined  
to form the composite refractive index profile versus  
film thickness shown in FIG. 7. Using the composite  
profile index of FIG. 7 for a total film thickness of  
16 micrometers on a glass substrate, the theoretical  
30 reflectance of such a device at various wavelengths is  
shown in FIG. 8. The extremely high reflectance at  
0.6  $\mu\text{m}$ , 0.8  $\mu\text{m}$ , and 1.0  $\mu\text{m}$  is evident in FIG. 8. In  
a similar manner, other coatings may be formed with  
other index profiles which are analytically synthesized  
35 to provide particular optical characteristics.

1           In addition, the photochemical vapor deposition  
process of U.S. Patent No. 4,371,587 can be used to  
produce many different oxide films, such as  $\text{SiO}_2$ ,  
5            $\text{TiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Ta}_2\text{O}_5$ , and  $\text{SnO}_2$ . Further, such a  
process can be used to provide a film structure that  
consists of two oxides with compositions that change  
gradually and continuously from one oxide to another.  
For a composite oxide film of  $\text{SiO}_2$ , with a refractive  
10           index of 1.45, and  $\text{TiO}_2$ , with a refractive index of  
2.55, the maximum index modulation achievable is 1.1,  
as compared to the 0.45 modulation achieved in the  $\text{SiO}_x$   
oxide system. The indices of some other useful oxides  
are 1.76 for  $\text{Al}_2\text{O}_3$ , and 2.18 for  $\text{ZrO}_2$ .

          Finally, as a practical matter, preliminary  
15           analysis has shown that the tolerance on the thickness  
and index variation are higher for the graded index film  
structure of the present invention than for a prior art  
multilayer quarterwave stack coating. It is anticipated  
that if a reasonably precise monitoring system for  
20           thickness and refractive index is installed, the  
photochemical vapor deposition process of the present  
invention will produce coatings with excellent  
reflectance, and showing minimum degradation due to  
the random error associated with the deposition process.

25           There are several advantages in forming a reflec-  
tive diffraction optical element for use as a filter  
by the process of the present invention. First,  
the filter is formed of an oxide material which is  
inherently stable in high humidity and over a  
30           wide temperature range, whereas conventional gelatin  
holograms are not. In addition, the  $\text{SiO}_x$  formed by  
the photochemical vapor deposition process has exhibited  
superior adhesion on glass, as well as plastics such  
as polycarbonate, and conforms to the shape of the  
35           substrate surface. The latter two properties make the

1 process of the present invention particularly well  
suited for the fabrication of head-up display combiners  
or night vision visors on curved substrates. Moreover,  
the  $\text{SiO}_x$  of the present invention can be deposited at  
5 a temperature sufficiently low (e.g. 30 to 200°C) so  
as to avoid thermal degradation of a plastic substrate,  
which makes possible the use of light weight plastic  
substrates in laser eye protection devices and head-up  
display devices. Further, the  $\text{SiO}_x$  formed as described  
10 herein possesses excellent optical and mechanical  
properties, such as good surface morphology and low  
pinhole or defect density, which result in reduced  
optical scattering. In addition, the low defect density  
of such an oxide makes it less susceptible to laser  
15 radiation damage. Further, by the process of the  
present invention, a continuously graded index optical  
material is deposited, and, thus, avoids the previously  
discussed prior art problems, such as reduced trans-  
mission, optical scattering, and thermal damage, caused  
20 by the juxtaposition of discrete layers of differing  
composition. By using the continuously graded index  
reflective coating of the present invention, the prior  
art problems of localized concentration of mechanical  
stresses as well as a concentration of the electric  
25 field are avoided. It has been analytically determined  
that the peak electric field in a filter with a  
sinusoidal profile is less than the peak electric  
field encountered in a square-wave multilayer filter  
having identical optical properties at the desired  
30 wavelength. In addition, the gradual change in  
composition in the material formed in accordance  
with the present invention reduces the thermal stress  
in the film when subjected to the high laser energy  
flux. This reduced thermal stress is expected to  
35 increase the laser damage threshold. The gradual

1 compositional change may also reduce the absorptance  
of the film. In addition, a better thermal match with  
the substrate may also be attained by adjusting the  
composition of the dielectric at the substrate interface  
5 so that the substrate and dielectric have compatible  
thermal expansions.

Moreover, the index of refraction of the material  
deposited in accordance with the present invention can  
be adjusted to a predetermined profile, which permits  
10 greater flexibility in the design of the optical element.  
In particular, the optical element of the present  
invention can be formed as a non-sinusoidal profile  
to provide high reflectance at several wavelengths, as  
previously discussed with regard to composite index  
15 profile devices. These latter devices are novel optical  
devices which have not been possible heretofore, such  
as a multiple-wavelength narrow band reflective diffraction  
optical element incorporated in a single deposited  
layer, which is useful in two-color head-up display  
20 combiners, laser eye protection visors, and reflective  
coatings on laser mirrors. In addition, the periodicity  
of the profile can be changed to reject any predetermined  
laser line within the spectral band of the deposited  
material, e.g. a peak wavelength from 0.3 to 2.5  $\mu$ m  
25 for  $\text{SiO}_x$ . Further, because the optical devices of  
the present invention can be constructed to provide  
high reflection of radiation within a narrow bandwidth,  
such devices have high transmission of the signal of  
interest and enhance the efficiency of signal detection.  
30 In addition, the devices of the present invention can  
provide high reflection over a wide wavelength region  
(e.g., 0.3 to 2.5 micrometers or greater for  $\text{SiO}_x$  or up  
to 5 micrometers for  $\text{Al}_2\text{O}_3$ ).

1 Further, the continuously graded index filters  
of the present invention can be fabricated by a  
photochemical vapor deposition process which is  
charge-free and avoids charge damage or radiation damage  
5 to sensitive devices, such as charge-coupled devices  
and compound semiconductor devices. In addition, such  
a process is performed at a low temperature, e.g., 30  
to 200°C, and avoids thermal damage to temperature-  
sensitive substrates, as well as stress caused by thermal  
10 mismatch of the substrate and deposited layer. Moreover,  
the material deposited by this photochemical vapor  
deposition process has excellent surface morphology,  
low pinhole density, low impurity content, low stress,  
large area uniform thickness, and conformity to substrate  
15 shape. The process of the present invention is highly  
reproducible and capable of large-scale production of  
uniform deposits. Finally, by the above-described  
process, a filter can be fabricated by a single step  
process, which reduces fabrication complexity  
20 and cost. It is particularly noteworthy that by the  
process of the present invention a filter which protects  
against multiple wavelengths of radiation can be  
fabricated in a single device by a single step process.

Further, the process of the present invention may  
25 be used to form a reflective coating on the surface of  
a mirror substrate to provide a surface with high  
reflectivity, low absorption, and low scattering. Such  
a highly reflective film is useful on mirrors provided  
in laser systems to reflect and guide the laser beam.  
30 In order to form such a reflective coating, the process  
previously described herein with particular reference  
to FIG. 5 is performed on a molybdenum or silicon  
mirror substrate, for example. The reflectance of this  
coating was measured at various wavelengths of incident  
35 radiation and the results are as shown in the curve of

1 FIG. 5 previously discussed. In order to improve  
adhesion and decrease stress, it may be advantageous in  
some cases to use a binder material, such as chromium  
5 or titanium, between the substrate and the graded index  
material. Such a metal binder may also be used to  
reduce the thickness requirement of the deposited film  
at a particular index modulation.

Furthermore, in accordance with a second process  
embodiment of the present invention, a continuously  
10 graded index optical material may be deposited by the  
photochemical vapor deposition process previously  
described herein except that a scanning laser beam or  
other collimated beam is used as the source of radiation  
to initiate the desired chemical reaction. The laser  
15 beam may be scanned across the surface of the substrate  
or other means may be used to effect relative movement  
of the laser beam with respect to the substrate, such  
as moving the substrate or adjusting the optical focusing  
system, as is known in the art and described, for example,  
20 in U.S. Patent No. 4,340,617. The laser beam or other  
collimated beam used has an output at the wavelength of  
radiation required to induce the desired photochemical  
reaction, as previously discussed herein. The beam is  
scanned across the surface of the substrate in a  
25 controlled manner so that one segment of the substrate  
at a time is exposed to the beam, with the segment size  
being determined by the beam diameter. The rate of  
deposition of the reaction product depends on the  
amount of reaction-inducing radiation to which the  
30 reactants are exposed. Consequently, if a given  
segment of the substrate has a longer exposure to the  
laser beam, that segment will have an increased amount  
of reactive product deposited thereon. Thus, a spatial  
variation of the deposition rate over the horizontal  
35 surface of the substrate can be achieved by controlling

1 the scanning speed or duty cycle and pattern of the  
laser beam. Since the deposition rate determines the  
thickness of the deposited layer, the thickness of the  
deposit and the refractive index thereof are likewise  
5 varied over the lateral surface of the substrate in  
accordance with the above-described scanning laser  
beam exposure. This variation in thickness may be in  
a continuous manner or in a stepped manner, as determined  
by the scanning pattern of the laser beam. The resulting  
10 structure has a continuously graded index layer as a  
function of thickness as previously described herein,  
and, in addition, the thickness of that layer varies  
in a predetermined pattern across the surface of the  
substrate. Since the amount of modulation within a  
15 given thickness determines the periodicity of the  
index modulation, the deposited layer on different  
segments of the substrate surface will have different  
periodicities. As previously discussed with regard to  
Equation (5) herein, the periodicity of the index  
20 modulation determines the peak wavelength of reflected  
radiation. Consequently, in accordance with this  
second process embodiment of the present invention,  
a diffraction optical element may be formed to have  
different peak wavelengths of reflection and/or thick-  
25 ness at various segments of the substrate surface.  
Such a structure is useful as a combiner in a head-up  
display system. Alternatively, in accordance with the  
second process embodiment of the present invention,  
the amount of reaction-inducing radiation to which  
30 predetermined segments of the substrate are exposed  
may be varied by using a flood source of ultraviolet  
radiation and a mask placed close to the substrate  
surface to prevent the radiation from striking the  
substrate at predetermined segments.

1           The first and second process embodiments of the  
present invention may be used to provide various optical  
elements with varying thickness and/or refractive index  
across the horizontal surface thereof, in addition to the  
5 modulated refractive index as a function of thickness as  
previously described. In one case, the refractive index  
is modulated as a function of thickness to provide a  
chosen  $\lambda_p$  as described with regard to the first process  
embodiment and, in addition, the thickness of the  
10 deposited layer is varied in a desired pattern, such  
as to form a convex surface, as described above with  
regard to the second process embodiment. The resulting  
structure has a horizontal variation in thickness and  
the same  $\lambda_p$  across the horizontal surface of the  
15 structure. A structure having such a variation in  
thickness provides a change in the efficiency of the  
diffraction element across the horizontal surface there-  
of, which is advantageous for compensating for spatial  
nonuniformity in the intensity of the incident radiation.  
20 In a second case, the thickness of the deposited layer  
is varied in a desired pattern as described immediately  
above, and, in addition,  $\lambda_p$  is varied across the  
horizontal surface of the layer as previously described  
with respect to an alternative of the first process  
25 embodiment of this invention. The resulting structure  
has a horizontal variation in thickness and variations  
in  $\lambda_p$  across the horizontal surface of the structure.  
In a third case, the thickness of the deposited layer is  
held constant and the refractive index of the deposited  
30 layer is varied across the horizontal surface of the  
substrate to produce variations in periodicity and  $\lambda_p$ ,  
as described above. In such a structure, variations in  
 $\lambda_p$  across the horizontal surface of the substrate are



1 not dependent on the thickness of the deposited layer.  
The constant thickness of such a structure may be  
achieved by placing a cover with an iris opening over  
the substrate and opening or closing the iris over a  
5 given segment of the substrate to control the amount  
of radiation striking the substrate segment, while at  
the same time altering the intensity of the radiation  
or the reactant gas flow rates in order to achieve the  
required modulated refractive index as a function of  
10 thickness and as a function of horizontal position on  
the substrate surface.

In summary, the following are some of the unique  
characteristics of the process of the present invention  
which provide conventional optical filter devices with  
15 improved performance, as well as novel filter devices  
heretofor unavailable:

- a. arbitrary profile of (complex) refractive  
index modulation by control of reactant  
flow rate ratio;
- 20 b. high index modulation;
- c. variable peak wavelength across the  
surface of the substrate;
- d. low temperature deposition;
- e. uniform coating conformed to substrate  
25 shape; and
- f. versatility in deposition materials.

In particular, some of the new and improved optical  
devices which may be formed in accordance with the  
30 present invention are:

- 1 a. wide angle optical filters with variable  
 $\lambda_p$  across the filter for wide angle  
receptions, such as bandpass filter,  
5 narrow band transmission or reflection  
filter, cut-off filter;
- b. absorption or transmission type apodizer  
to provide even intensity across the  
resultant beam, such as variable density  
10 neutral density transmission filter,  
variable reflection filter;
- c. surface grating with grating profile  
shaped by the UV light profile and/or  
the variable index through grating depth;
- d. variable index coating on substrates or  
15 fiber cores to form special optical  
devices, such as optical fibers or  
integrated optics elements;
- e. element for replication of masks and  
computer generated holograms;
- 20 f. IR and visible filter for laser hardened  
IR detector and solid state components,  
such as a laser protection filter for  
detectors, or for personnel laser eye  
protection;
- 25 g. narrow band, single color or multi-color,  
transmission or reflection or cut-off  
type filters;
- h. thin lens with variable surface profile  
and variable index throughout or across  
30 the lenses;
- i. anti-reflection, or high reflectivity  
filters on plastic substrates or on glass  
substrates;

1                   j. any of the above coatings on aspheric  
                  substrates; and

                  k. slanted fringe optical devices.

                  Moreover, the process of the present invention is  
5       not limited to the use of oxides of silicon, but may  
      include any of the oxides which may be deposited by the  
      process disclosed in U.S. Patent No. 4,371,587, previously  
      referenced herein. In addition, other materials besides  
10       oxides may be deposited as described herein by other  
      photochemical processes, such as silicon nitride by the  
      process disclosed in U.S. Patent 4,181,751, assigned to  
      the present assignee, and various sulfides by the  
      process disclosed in U.S. Patent 4,447,469, assigned  
15       to the present assignee. Further, combinations of  
      these various materials may be used, such as silicon  
      dioxide in combination with silicon nitride. As a  
      practical matter, the material deposited in accordance  
      with the present invention must be stable in the presence,  
      of air and water vapor.

20               Furthermore, the present invention is not limited  
      to photochemical vapor deposition processes, but includes  
      other known deposition processes in which the reactant  
      gas flow rate ratios are controlled as described herein  
      to provide a continuously graded index optical material  
25       with a predetermined index profile. For example, in a  
      thermal chemical vapor deposition process in which  
      reactants are heated to a sufficiently high temperature  
      to bring about a chemical reaction to form a desired  
      product, the gas flow rate ratio of the reactant gases  
30       is controlled in the manner previously discussed herein.  
      A type of thermal chemical vapor deposition of particular  
      interest in this regard is the deposition of an epitaxial  
      layer by metallo-organic chemical vapor deposition.

1 In a thermal evaporation or physical vapor deposition  
process in which two sources, such as zinc sulfide and  
zinc selenide, are heated to produce evaporation thereof  
and subsequent condensation on the substrate, the thermal  
5 evaporation of one source, such as zinc sulfide, is  
held at a constant rate while the thermal evaporation  
of the second source is varied as a function of time,  
in the manner discussed herein. Similar methods can be  
used in electron beam evaporation techniques and sputter  
10 evaporation techniques using two targets. Likewise,  
in a molecular beam epitaxial growth process in which  
an epitaxial layer of a material is grown by causing  
beams of atoms or molecules to impinge on the target,  
the relative proportion of the impinging beams can be  
15 altered as described herein to provide an epitaxial  
layer having a graded refractive index in a predeter-  
mined pattern.

#### EXAMPLE 1

20 This example illustrates the formation of a  
continuously graded index optical material in a pre-  
determined pattern suitable for use as a filter,  
in accordance with the first process embodiment  
of the present invention as previously described herein.  
25 The photochemical vapor deposition process and apparatus  
described in U.S. Patent No. 4,371,587, previously  
referenced herein, were used to deposit a film of  $\text{SiO}_x$   
on a glass slide substrate having dimensions of 2 inches  
(5.08 cm) by 3 inches (7.62 cm) and 40 mils (0.10 cm)  
30 thick. The vapor phase reactants were silane ( $\text{SiH}_4$ )  
and nitrous oxide ( $\text{N}_2\text{O}$ ), and mercury was used as a  
photosensitizing agent. The reaction-inducing radiation  
was at a wavelength of 2537Å; the substrate temperature  
was 100°C; and the total operating pressure was approxi-  
35 mately one torr (millimeter of mercury). Alternatively,

1 an operating pressure within the range of about 0.1 to  
50 torr may be used. The reactant gases  $\text{SiH}_4$  and  $\text{N}_2\text{O}$   
entered at one end of the deposition chamber through  
mass flow controllers which control the flow of the  
5 reactant gases. The flow of reactant gases was  
initiated and followed by adjustment of total pressure,  
gas flow rates, gas flow ratios, and substrate  
temperature. Gas pressure during deposition was kept  
constant and the substrates were positioned so that  
10 there was minimum disruption of the laminar gas flow  
pattern. Upon system equilibration, the deposition of  
 $\text{SiO}_x$  was initiated by transmission of the reaction-  
inducing radiation into the reaction chamber, using the  
data of FIG. 3, previously discussed, to determine the  
15 required intensity of light. A bank of four low-pressure  
mercury vapor lamps, obtained from Canrad-Hanovia, Inc.  
of Newark, New Jersey, was used as the source of light  
and was located approximately 2.75 inches (6.99 centi-  
meters) from the substrate surface. The gas flow rate  
20 of  $\text{N}_2\text{O}$  was held constant at 62.0 sccm and the gas  
flow rate of  $\text{SiH}_4$  was varied in a controlled manner  
from 0.90 sccm to 3.5 sccm.

Using the previously discussed data of FIG. 1  
and a graph generated from experimental data to show  
25 the change in flow rate with time, the flow rate of the  
silane reactant was altered with time by manual turning  
of the gas flow controller knob at a predetermined rate  
to produce an oxide film with a refractive index that  
varied in a continuous sinusoidal pattern from 1.45 to  
30 1.63, for a total of 16 periods, producing a peak  
wavelength at  $1.48\mu\text{m}$ . The measured spectral reflectance  
of the holographic filter so formed is presented in  
FIG. 5, showing an 81.3 percent peak efficiency, and  
this data has been previously discussed in detail.

1     Such a structure is useful, for example, as a highly  
reflective coating on the surface of a mirror used in a  
laser system, in order to provide maximum transmission  
of the laser signal and minimum laser damage to the  
5     mirror.

#### EXAMPLE 2

10     This example illustrates the formation of a layer  
of a continuously graded index optical material on  
the surface of a substrate in accordance with the  
process of the present invention, in which a composite  
oxide film of silicon dioxide ( $\text{SiO}_2$ ) and titanium  
dioxide ( $\text{TiO}_2$ ) is formed, to provide a maximum  
refractive index modulation of 1.1.

15     The process described in Example 1 above is  
followed except that titanium tetrachloride ( $\text{TiCl}_4$ )  
is used as an additional vapor phase reactant. As  
described in U.S. Patent No. 4,371,587, the atomic  
oxygen formed by the photochemical dissociation of the  
20     nitrous oxide reacts with the  $\text{TiCl}_4$  to form titanium  
dioxide. In accordance with the present invention,  
the gas flow rate of nitrous oxide is held constant  
and the gas flow rates of  $\text{SiH}_4$  and  $\text{TiCl}_4$  are varied  
in a controlled manner with respect to each other and  
25     with respect to the nitrous oxide. The required flow  
rates of the  $\text{SiH}_4$  and  $\text{TiCl}_4$  are determined from  
experimental data which indicate the dependence of the  
refractive index of the deposited material on the flow  
rates. The  $\text{SiH}_4$  and  $\text{TiCl}_4$  reactants each react with  
30     the atomic oxygen to form  $\text{SiO}_2$  and  $\text{TiO}_2$ , respectively,  
which deposit simultaneously on the substrate to  
provide a composite oxide film comprising  $\text{SiO}_2$  and  
 $\text{TiO}_2$ . The composition of the composite oxide may  
vary from pure  $\text{SiO}_2$  with a refractive index of 1.45

1 along the continuum to pure  $\text{TiO}_2$  with a refractive  
index of 2.55. The resulting composite oxide film has  
a continuously graded refractive index as a function  
of thickness, with a maximum index modulation of 1.1.

5

### EXAMPLE 3

This example illustrates the formation of a layer  
of a continuously graded index optical material on the  
surface of a glass substrate in which the index also  
10 varies in a predetermined pattern across the surface of  
the substrate, in accordance with the second process  
embodiment of the present invention as previously  
described herein. The general procedure described  
in Example 1 is followed except that the source of  
15 radiation is a scanning laser beam comprising an  
argon-fluoride tunable excimer laser and associated  
electronics and optics obtained from Lumonics of New  
Jersey and a raster scanning mechanism obtained from  
General Scanning, Inc. of Watertown, Massachusetts.  
20 Under computer-control, the laser beam is scanned in a  
predetermined pattern across the horizontal surface of  
the substrate, as described in U.S. Patent No. 4,340,617,  
for example. There is deposited on the substrate a layer  
of a material, such as  $\text{SiO}_x$ , which has a continuously  
25 graded refractive index as a function of the thickness  
of the deposited layer and also a graded refractive  
index radially across the horizontal surface of the  
substrate in a pattern corresponding to the pattern of  
the scanning laser beam.

30 While the present invention has been particularly  
described with the respect to the preferred embodiments  
thereof, it will be recognized by those skilled in the art  
that certain modifications in form and detail may be  
made without departing from the intention and scope of  
35 the invention. In particular, the scope of the invention

1 is not limited to the photochemical vapor deposition  
of a continuously graded index layer of oxides of  
silicon, which was used merely as an example, but is  
intended to include oxides, nitrides, sulfides, and  
5 other materials and combinations thereof, with suitable  
optical properties. In addition, while the preferred  
process embodiment of the present invention has been  
referred to as a "photochemical vapor deposition  
process", it is not intended to limit the present  
10 invention to the process embodiment of U.S. Patent  
No. 4,371,587 in which atomic oxygen is photochemically  
generated; rather it is intended to include any oxide  
formed by any process embodiment of the latter patent.

Moreover, while the present invention has been  
15 described with reference to a particular photochemical  
vapor deposition process which is specifically controlled  
in order to form an oxide having a continuously graded  
refractive index in a predetermined pattern, it will be  
recognized that other known deposition processes for  
20 forming oxides, as well as other materials, may be  
similarly controlled to achieve a deposited layer having  
the same graded index profile and optical properties as  
described herein. Other materials which may be used  
to form the graded index layer are characterized by  
25 being dielectrics which are transmissive in the wave-  
length range of interest.

Further, the present invention is not limited to  
the particular refractive index profiles specifically  
disclosed herein, but is intended to include any pre-  
30 determined profile. In addition, it is not intended  
to limit the present invention to the particular process  
details described herein, but to include any variations  
in process parameters as may be required in order to  
achieve the desired refractive index profile in the  
35 deposited material.



1           Finally, the present invention is not limited to  
the uses of the continuously graded index materials as  
specifically set forth herein, but includes structures  
comprising such continuously graded index materials  
5           which may be used for any purpose.

Referring now to FIG. 9, a novel diffraction-type  
optical combiner is disclosed. The improved performance  
and relatively simple structure of the combiner 40 are  
well suited for applications such as HUDs or HVDs. The  
10          combiner 40 illustrated in FIG. 9 comprises a substrate  
45, fabricated from a material such as glass or plastic.  
A diffraction coating 50 is formed on the surface 46 of  
the substrate, and may comprise a gelatin hologram or a  
graded-index coating. The graded-index coating is  
15          preferably formed in accordance with the photochemical  
vapor deposition process described hereinabove or some  
other deposition process. An antireflective coating  
48 is formed on the other surface 47 of the substrate 45.

The surfaces 46 and/or 47 can have a plane or  
20          spherical contour, but preferably have an aspheric  
contour selected to compensate or balance aberrations  
in the display system in which the combiner 40 is  
employed. The coating 50 can provide a narrow band,  
high reflectivity response, similar to a conventional  
25          gelatin hologram formed on a spherical substrate.  
However, the gelatin hologram coating has improved  
optical performance over conventional gelatin holograms  
formed on spherical substrates. This improved  
performance results from the elimination of the slant  
30          fringes, the substrate contour providing the asphericity  
necessary for aberration compensation rather than the  
hologram itself. The considerations and principles which

1 enter into determining the specific shaping of the  
aspherically contoured surface needed to achieve given  
design criteria are the same well-known considerations  
and principles which enter into determining the desired  
5 orientation of the fringes in a gelatin hologram with,  
of course, appropriate conventional compensation for  
any differences in refraction due to changes in the  
medium.

10 The added flexibility in the coating design and  
fabrication using graded index coatings allows the  
production of improved performance combiners, such as  
those used to make high see-through and multiple color  
displays, and thus has certain advantages over the  
gelatin hologram coating.

15 The graded-index coating can be applied directly  
on plastic surfaces such as polycarbonate, and is inert  
to environmental effects such as humidity and temperature  
in the normally specified ranges, unlike the gelatin  
hologram. These two characteristics enable the graded-  
20 index coating to be applied directly to the surface 46  
of the substrate 45, which provides a major optical  
advantage. Since the surface 46 is the surface facing  
the observer's eye 58, as illustrated in FIG. 9, the  
combiner 40 substantially reduces the strong displaced  
25 second (ghost) image often encountered with a laminated  
gelatin holographic combiner. The intensity of the  
reflection from the second surface 47 is generally  
several orders of magnitude down from the intensity of  
the main image reflected from surface 46 and, therefore,  
30 is not a significant problem affecting the practical  
use of the combiner in a HUD or HVD system. Moreover,  
the antireflective (AR) coating 48 is applied only to  
surface 47 of the substrate 45, while the gelatin type  
of HUD or visor combiner requires AR coatings on both  
35 sides of the combiner.

1           The reduction in intensity of the ghost image is  
illustrated in FIG. 9. The display light source may  
typically comprise a CRT 55. The narrow band light  
5           generated by the CRT is incident on the combiner 40  
along ray 56. The coating 50 may typically be adapted  
to reflect 80% of the incident light from the source 30  
back along ray 57 to the observer's eye 58. The small  
portion of the display source light which is not  
reflected by the coating 20 is transmitted along ray  
10          56a to the interface of the substrate 45 and the AR  
coating 48. A typical AR coating typically reflects  
only about .5% of the incident light and transmits the  
remaining light. The reflected light travels along ray  
15          57a. The coating 50 reflects 80% of the light incident  
along the ray 57a and transmits only 20% of the incident  
light. The intensity of the second image along ray 57a  
is only (20%) (.5%) (20%), or .02% of the intensity of  
the light incident on the combiner 40 from source 55.  
Thus, the intensity of the reflected second image is  
20          far less than the intensity of the primary reflected  
image.

          The ghost image performance of the combiner 40  
illustrated in FIG. 9 is contrasted with a conventional  
gelatin holographic combiner, comprising at least five  
25          layers, two outer AR coatings formed on outer surfaces  
of two glass substrates, which in turn sandwich the  
gelatin hologram. Even assuming comparable performance  
for the AR coating (.5% reflectivity) and 80% reflectivity  
for the gelatin hologram at the wavelength of the source  
30          light, there are now five interfaces to be considered,  
and three significant components of the displaced image.  
The combined intensity of the three secondary components  
is .84%, or a factor of 40 higher as compared with  
35          .02% for the combiner shown in FIG. 9.

1           The combiner illustrated in FIG. 9 can also provide  
improved see-through performance, larger exit pupil  
size, multiple color and optimized display efficiency.  
These improved performances directly result from the  
5       flexible design and fabrication processes achievable  
through deposition techniques such as the photochemical  
vapor deposition process described above, which are  
capable of depositing coatings with graded-index profiles.

For HVD or HUD applications, it is desirable for  
10       the viewer to see clearly the external environment  
through the visor or HUD combiner and that the color of  
the external scenes not be tinted by the combiner.  
This requires that only a small portion of the external  
light incident on the combiner be reflected by the  
15       diffraction coating on the combiner. If the reflectivity  
response of the combiner is not narrow band, or if there  
are significant sidelobes in the reflectivity response  
about the peak efficiency wavelength, then the external  
environment will appear tinted to the viewer and the  
20       see-through performance of the combiner will be degraded.

The index profile of a graded-index coating can  
be designed to provide a narrow band, high reflectivity  
spectral response with side-lobe reflection minimized  
so that the see-through performance is improved. This  
25       feature is illustrated in FIGS. 10 and 11.

FIG. 10 is a graph plotting the reflectivity  
function of both conventional gelatin holograms and  
graded-index holograms as a function of the wavelength  
of the incident light. In FIG. 10 the reflectivity of  
30       the gelatin hologram is indicated by the broken line  
and the reflectivity of the graded-index coating is

1 indicated by the solid line. The index profile of the  
gelatin hologram is sinusoidal. However, the graded-index  
coating is designed to have a non-sinusoidal profile  
which will yield suppressed sidelobes in the spectral  
5 reflectance profile of the coating. Typical peak  
reflectivity values of 80%, centered at 543 nm, are  
readily achievable by both types of coatings. However,  
the gelatin hologram reflectivity exhibits typical  
sidelobes of appreciable reflectivity for light outside  
10 the narrow band wavelength range of interest. The  
sidelobes in the reflectivity function indicate that  
considerable light from the external environment will  
be reflected by the combiner and not transmitted to  
the observer's eye, thus degrading the see-through  
15 performance. On the other hand, the graded-index  
coating can be designed and fabricated to minimize the  
sidelobes in the reflectivity response, so that the  
see-through performance is improved.

By employing a graded-index coating with a  
20 particular non-sinusoidal index profile, the peak  
reflectivity response can be broadened so that a wider  
bandwidth  $\Delta\lambda$  of wavelengths is reflected with at least  
80% reflectivity. To achieve a corresponding broadening  
of the reflectivity response for a gelatin hologram  
25 coating would typically require higher peak reflectivity,  
and consequent increase in the sidelobe level, resulting  
in undesirable refraction in the sidelobe spectral  
region. This effect is illustrated in FIG. 11 where  
the solid line depicts the reflectivity response of a  
30 graded-index coating with a non-sinusoidal index profile  
and the upper broken line depicts the reflectivity  
response of a gelatin hologram designed to provide the  
same bandwidth but with higher peak efficiency of 95%.

1           The graded index coating allows great flexibility  
in balancing the bandwidth, sidelobe and reflectivity  
response of the combiner according to the requirements  
of particular applications. For example, a bandwidth  
5  $\Delta\lambda$  (as depicted in FIG. 11) on the order of 20-30 nm can  
be designed with acceptable reflectivity, and low sidelobe  
level. This allows the use of the phosphor P53 for  
the CRT light source, which emits light whose wavelength  
is centered at 543 nm within 5-10 nm range. This is  
10 in contrast to the P43 phosphor which is used in CRTs  
to emit light at wavelengths centered at 543 nm but  
within a 2-3 nm range. Thus, with the broadened  
reflectivity response, the image brightness may be  
increased.

15           The bandwidth increase achievable with non-  
sinusoidal graded-index coatings provides another  
performance advantage, an increase in the angular  
reflectivity function. The angular reflectivity function  
characterizes the reflectivity as a function of the  
20 angle of incidence for a given wavelength of the  
impinging light. If the reflectivity response is high  
over a wider band of incident angles, the exit pupil  
size is correspondingly larger.

          The increase in exit pupil size can be maximized  
25 through control of two parameters. Increasing the  
magnitude of the index modulation (i.e., the difference  
between the highest and lowest index) through the thick-  
ness of the coating for a given non-sinusoidal, graded-  
index coating is found to result in broadening of the  
30 peak reflectivity response, and correspondingly the  
angular reflectivity bandwidth. Moreover, the graded-  
index coating can be fabricated from substances having  
a higher average index of refraction than the gelatin  
hologram. For example, a graded-index coating formed

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1 from layers of  $\text{SiO}_x$  and  $\text{SiO}_2$  can be designed with an  
average index of 1.75, compared to the typical gelatin  
hologram with an average index of about 1.50. This  
5 results in an exit pupil area which is about 30% larger  
than the gelatin hologram.

A requirement of a combiner used in a typical  
display system is that it be able to reflect light from  
the display source which is incident upon the combiner  
at angles of incidence which vary as a function of  
10 position on the combiner. A holographic or interference-  
type coating is designed to reflect a narrow band  
range of wavelengths and to transmit light of wavelengths  
outside the narrow band range. The narrow band range,  
centered at a particular wavelength, shifts as the  
15 angle of incidence is shifted from the normal direction.  
The center frequency at normal incidence is typically  
referred to as the hologram wavelength. Because the  
display source light typically is not incident normally  
at the combiner surface, and in fact the angle of  
20 incidence varies across the surface of the combiner,  
the peak wavelength must be varied accordingly across  
the combiner in order to maximize the display efficiency.  
Both the holographic gelatin combiner and the graded-index  
combiner are able to meet this requirement.

25 The graded-index coating can be generated on the  
substrate so that the peak efficiency hologram wavelength  
varies at different points on the combiner to achieve  
maximum display efficiency in the designed viewing  
area. This effect is illustrated in FIG. 12. The  
30 optical combiner 60 comprises a substrate 61 on which a  
graded-index coating 62 is formed. A display source 63  
generates display light at wavelength  $\lambda_0$ . Three rays  
64, 65, 66 of the display light are shown incident  
across the surface of the coating 62 formed on the  
35 combiner 60. The respective non-equal angles of

1 incidence for rays 64, 65, 66 are  $\theta_1$ ,  $\theta_2$ ,  $\theta_3$ . At  
the points of incidence, the respective hologram  
wavelengths are  $\lambda_1$ ,  $\lambda_2$ ,  $\lambda_3$ , designed such that  
the peak efficiency wavelength reflected back to the  
5 observer's eye at the respective non-normal angles of  
incidence  $\theta_1$ ,  $\theta_2$ ,  $\theta_3$  is  $\lambda_0$ .

The same effect can be obtained by using an  
aspheric substrate contour with any diffraction coating,  
such as a gelatin coating, or to combine the aspheric  
10 substrate contour with a graded-index coating.

Thus, the combiner 40, in accordance with the  
invention, may comprise a substrate having an aspheric  
surface, and a diffraction type reflective coating for  
reflecting radiation within one or more predetermined  
15 narrow band ranges of wavelengths impinging on the  
layer. The coating can comprise a gelatin hologram or  
other type of diffraction coating. The preferred  
embodiment, however, comprises an aspheric substrate  
of a lightweight plastic material, on which a graded-  
20 index coating is formed. The asphericity can be designed  
in accordance with the requirements of a specific  
optical system to compensate or balance optical  
aberrations in the system. Moreover, the graded-index  
profile can be designed to provide specific reflectivity  
25 responses, to provide multiple color capability, improved  
see-through, enlarged pupil size, and increased efficiency.

The fabrication of aspheric plastic substrates  
is well known in the ophthalmic art. The aspheric  
surface is formed, for example, by a casting process,  
30 utilizing a master (for example, glass or metal) having  
the aspheric surface formed thereon by conventional  
grinding and polishing techniques. The master is then  
employed to make a nickel plate replica, one for each  
surface of the substrate (each surface may have a  
35 different contour). The nickel plate replicas of the  
surfaces may then be utilized to cast a plastic substrate.



1           This method for fabricating the plastic substrate  
is generally illustrated in FIGS. 13 and 14. A desired  
aspheric surface contour 106 is formed on a glass  
substrate 105 to define glass master 105. Using the  
5           glass master, the nickel plate replica 110 of the  
surface contour 106 is formed, also by conventional  
techniques known to those skilled in the art.

          By the same process, a second nickel plate replica  
110a can be formed using a second master. The  
10          two nickel replicas 110, 110a may then be employed as  
cast surfaces to cast a premeasured quantity of an  
unpolymerized acrylic (or CR-39) compound 115 into a  
substrate whose contours replicate the contours of the  
nickel replica 110, 110a. The casting method includes  
15          disposing a compressible gasket retainer 120 around  
the periphery of the contours 106, 106a, sandwiching  
the quantity of unpolymerized acrylic compound 115  
between the two plates and retained by the gasket 120,  
setting the plates in an elevated temperature bath so  
20          that the acrylic compound polymerizes, usually shrinking  
by about 13%, to assume the contours 110, 110a. The  
plates may then be removed from the elevated temperature  
bath and separated to remove the formed casting.

          The casting method provides a relatively low-cost  
25          technique to fabricate the aspheric substrates in  
production quantities. The parts may also be fabricated  
by injection molding. In contrast, fabrication of  
aspheric glass substrates in production quantities  
would be prohibitively expensive using conventional  
30          techniques.

1           One application to which a combiner as illustrated  
in FIG. 9 may be advantageously employed is in helmet  
mounted visor displays (HVDs) used by aircraft flight  
personnel. As is known, images from a light source  
5   such as a CRT may be used to display symbology information  
or reticle information on a see-through visor, so that  
the symbology is presented to the helmet wearer as he is  
viewing the external environment through the visor.

10           The general arrangement of a biocular visor system  
in accordance with the invention is illustrated in the  
schematic block diagram of FIG. 15. In this figure,  
light is shown emanating from an object source 210,  
which may be a CRT, and directed by an image folding  
prism 211 via a relay lens 212 to a beam splitter 213.  
15   The beam path from the source 210 to the image folding  
prism 211 is shown unfolded for convenience of  
illustration. At the beam splitter 213, the incident  
light is split into two beams by splitter 213, which  
directs the beams laterally to a pair of folding members,  
20   shown as wing mirrors 214.

25           The mirrors 214 redirect the respective beams  
through a plastic window 216 toward the respective  
aspheric mirrors comprising the combiners 215 which are  
optical elements as shown in FIG. 9. The selectively  
reflective properties of the combiners 215 cause the  
30   object source light to be redirected toward the user's  
eyes through exit pupils 217. Each eye views the  
image at the corresponding exit pupil as a virtual  
image at infinity. The intermediate images, represented  
by the broken lines 216, are developed between the  
35   relay lens 212 and the combiners 215.

1           One specific, preferred HVD embodiment is  
represented schematically in further detail in FIGS.  
16-18. The arrangement of the principal elements of  
the biocular system is shown in FIG. 16 in relation to  
5 the wearer's head, with the helmet omitted for simplicity.  
The system comprises a miniature cathode ray tube (CRT)  
source having a flat display element 220 bearing a  
phosphor on its inner surface 221. As indicated in  
FIG. 16, the normal to the CRT plate 220 is aligned at  
10 27.039° to the reference line 222 of the system.

Folding prism 223 is adjacent the CRT 220. The  
entrance face 224 of the prism 223 is orthogonal to the  
reference line 222, while the exit face 225 is at a  
wedge angle of 4.554° to the reference line 222. The  
15 light from the cathode ray tube is internally reflected  
within the prism 223 which is spaced so that the entrance  
face 224 is located at a point which is .411 inches  
from a zero reference line 226, which is orthogonal to  
the reference line 222 at the outer surface of the CRT  
20 face 220.

Next to the folding prism 223 is the relay lens  
227 comprising three lenses 228, 229, 230 in a modified  
Cooke triplet, together with a fourth lens 231. The  
two outer lenses 228 and 231 of the relay lens 227 have  
25 aspheric surfaces while the lens 230 is a meniscus  
lens with spherical surfaces. The mounting of the  
relay lens off-axis serves to bend the axial ray 232  
into coincidence with the reference line 222.

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1           The light transmitted by the relay lens 227 is  
then directed to a beam splitting prism 223. The front  
surfaces 235 (FIGS. 16 and 17) have a concave curvature.  
The prism 233 splits the light transmitted by the relay  
5   lens 227 into a pair of laterally directed images.  
These images are reflected by wing mirrors 236, 237 (shown  
in FIG. 17) on opposite sides of the beam splitting  
prism 233 and sent to the respective combiners 240  
through window 238 employed to seal the relay optics  
10 from the external environment. Rays from a particular  
field point are reflected by the combiner 240 toward  
the user's eye through an exit pupil 248 (represented  
by lines 248 in FIG. 16 and FIG. 17).

15           The view in FIG. 17 is taken from the upper right  
of FIG. 16, parallel to the reference line 222 and the  
aligned faces of the folding prism 223 and beam splitting  
prism 233. For simplicity, the wing mirrors 236 and  
237 are not shown in FIG. 16.

20           The axis (represented by line 227a) of the relay  
lens 227 comprising the lens elements 228-231 is at an  
angle of 8.630 degrees to the reference line 222, and  
the point at which the axis 227a intersects the surface  
228a is displaced from the reference line 222 by 0.22  
inches.

25           As indicated in FIG. 16, the aspheric lens 228 is  
mounted such that the point at which its surface 228a  
is intersected by the axial ray 232 is located 1.645  
inches from the zero reference line 226. The face 234  
of the prism 233 is 2.941 inches from the zero reference  
30 line 226, while the point at which the reflected axial  
ray 232 exits the combiner 240 is 7.526 inches from  
the zero reference line 226. The combiner 240 is

1 oriented such that its element axis in the plane of  
FIG. 16 forms an angle of 30.431 degrees with the path  
of the axial ray exiting the combiner 240 (extending in  
the direction of the exit pupil 248).

5 The location of the wing mirrors 236 and 237 is  
limited in the disclosed embodiment by a requirement  
for a 40° see-through capability and the necessary head  
clearance. This in turn fixes the location of the beam  
splitting prism 233. First order and packaging  
10 consideration (especially the need for a long back  
focus to allow the inclusion of the fold prism 223)  
dictate that the aperture stop fall slightly before the  
prism 233. This is also one of the positions of the  
aperture stop for which the relay lens 227 can most  
15 readily be designed for superior performance. However,  
with minor modifications of the design, the aperture  
stop may be located before or within the relay lens  
117 if desired.

Sufficient eye relief has been incorporated into  
20 the display system to allow the user to wear glasses  
and a standard oxygen mask. Given the eye relief and  
aperture stop location desired, the focal length of the  
combiner 240 and the magnification of the relay lens  
227 are readily determinable. Because the user looks  
25 through the combiner 240, see-through distortion is  
carefully controlled.

30

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1           A summary of the optical characteristics of the  
particular embodiment of the display system depicted in  
FIGS. 15-19 is set forth in Table I.

5                           TABLE I

	<u>Parameter</u>	<u>Value</u>
	System	
10	Horizontal field of view	40°
	Vertical field of view	30°
	Exit pupil width (truncated circle)	15mm
	Exit pupil height (truncated circle)	10mm
15	Effective focal length	21.6mm
	Horizontal f-number	1.44
	Vertical f-number	2.16
	Eye Relief	98mm
	CRT diameter	19mm
20	Exit pupil separation	62.5mm
	Wavelength	542-550
	Internal	
25	Combiner focal length	50.8mm
	Combiner f-number	3.4
	Combiner bend angle	60.8°
	Relay lens f-number	1.01
	Relay lens field of view	37°
30	Approximate relay lens width	29mm

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1           It will be apparent to those skilled in the art that  
the various parameters set forth above with respect to  
the particular embodiment depicted in FIGS. 15-18 are  
selected in accordance with acceptable design principles  
5       and may be varied in accordance therewith, in a manner  
well known to those skilled in the art, to adapt the  
design to various applications and specifications with-  
out departing from the scope of the present invention.  
Other parameters of the system, not specified, such as  
10       the prescriptions for the lens surfaces of the relay  
lens 227 and the surface of combiner 240, may be chosen  
in accordance with such principles to satisfy any  
particular design specifications. These principles  
are understood to those skilled in the art, as evidenced  
15       by optical engineering textbooks such as "Modern Optical  
Engineering," by Warren J. Smith (McGraw-Hill, Inc.  
1966). It will also be apparent to those skilled in  
the art that separate optical channels, each with a  
design similar to that illustrated in FIGS. 15-17, can  
20       be used to provide a separate display to each eye by  
simply eliminating the folding mirror 236 and prism 233.  
This dual separate channel configuration provides the  
capability for a stereoscopic display system.

          The HVD system depicted in FIGS. 15-19 has  
25       substantial advantages over the HVD systems employing  
gelatin holograms. The enhanced optical performance  
achieved by graded-index combiners is one such advantage.  
While the specific performance parameters to be optimized  
are application dependent, it is apparent that the  
30       aspheric combiner can be optimized to provide improved  
image quality substantially resulting from the  
minimization of the flare and chromatic dispersion  
inherent in a gelatin holographic combiner, larger exit  
pupil size, improved see-through and efficiency, larger  
35

1 field of view and elimination of ghost images. Moreover,  
the combiner can be fabricated from lightweight  
polycarbonate, substantially reducing the weight of the  
combiner and the burden on the visor wearer.

5 Another application for a combiner as shown in  
FIG. 9 is in head-up displays (HUDs) for aircraft  
cockpit use. A general schematic diagram of a HUD  
employing the novel combiner is depicted in FIG. 20.  
The aircraft has a canopy 260 and a surface 266. A  
10 combiner 270 comprises a substrate 269 and a diffraction-  
type coating 268. A cathode ray tube 278 provides an  
image source at object plane 276. The object plane is  
imaged through a relay lens 280 to a folding prism 282  
having a surface angled to direct the rays over the  
15 surface of the combiner 270. The rays are then diffracted  
by the combiner 270 to the pilot's eye 284.

A head-up display employing the combiner comprising  
an aspheric substrate and graded-index diffractive  
coating has several advantages over systems employing  
20 gelatin holographic coatings. One advantage is the  
weight reduction, resulting from the elimination of the  
glass layers which are typically employed to protect  
the gelatin hologram. With a plastic substrate, the  
weight savings can be significant. Further, the plastic  
25 substrate does not present the safety risk of shattered  
glass inherent in gelatin holograms combiners; with a  
plastic substrate the combiner is birdstrike safe.  
This in turn permits the combiner to be located closer  
to the canopy than is permitted with glass combiners,  
30 allowing the design of head-up displays with greater  
look-up capability. Other advantages of the head-up  
display system employing the aspheric combiner are  
reduced see-through distortion and ghost images and  
improved image quality. Moreover, the lower cantilevered  
35 mass of the lightweight combiner increases the stiffness  
of the combiner and reduces its sensitivity to vibration.



1           The following summarizes some of the advantages  
resulting from combiners fabricated in accordance with  
the principles discussed herein:

- 5           a. the strong double image due to the first  
surface reflection in a gelatin combiner is  
eliminated because the graded-index coating is  
located on the outermost surface. This placement  
of the graded-index coating also eliminates the  
need for an antireflective coating on one side  
10          of the combiner;
- b. the combiner can provide improved optical  
performance such as higher see-through and  
efficiency and larger exit pupil area and field of  
view due to the flexibility in coating design and  
15          fabrication;
- c. the combiner is a lightweight assembly  
because only one substrate is used, which may be  
lightweight polycarbonate instead of glass. No  
cover lamination is needed, as compared with the  
20          gelatin HUD or visor display;
- d. it is easier to fabricate a multiple-color  
HUD combiner or visor display combiner;
- e. the combiner eliminates image-degrading  
flare and chromatic dispersion caused by slanted  
25          fringes in holographic gelatin combiners, which  
allows the use of broader-band display sources  
(CRTs) resulting in brighter, more efficient  
displays;
- f. the graded-index combiner with an oxide  
30          coating is environmentally stable and may, there-  
fore, be applied on plastic, as well as on glass  
substrates;
- 35

1           g. the fabrication of the combiner is more  
cost-effective on a production level than gelatin  
combiners. Tooling costs may also be lower;

5           h. the reduced combiner thickness results in  
less see-through distortion even when both surfaces  
are asperic;

10           i. with only one wedge tolerance to consider  
instead of several, there is less difficulty in  
eliminating fabrication related see-through dis-  
tortion, boresight error and, in the case of  
helmet visor displays, binocular disparity;

          j. for head-up displays, the lower canti-  
levered mass of the lightweight combiner makes  
the combiner stiffer and less vibration sensitive;

15           k. the plastic substrate of the combiner  
provides a quality of being birdstrike-safe,  
thereby providing the capability of designing a  
head-up display with enhanced look-up capability;

20           l. the combiner when used in a helmet visor  
display is lighter weight than gelatin hologram  
visors, and has reduced see-through distortion  
and ghost images, with an overall improved optical  
MTF and image resolution.

25           Although the invention has been described with  
reference to specific embodiments, the exact nature and  
scope of the invention is defined in the following  
claims.

30  
  
CBB:cal  
[20-7]

CLAIMSWhat is Claimed is:

- 1           1. An optical structure comprising:
  - a) a substrate having at least one aspheric surface; and
  - b) a layer formed on said surface, said layer
- 5           comprising a diffraction-type reflective coating for reflecting radiation within one or more predetermined narrow band ranges of wavelengths impinging on said layer.
- 1           2. The structure of Claim 1 wherein said layer comprises a gelatin hologram layer which reflects radiation within a predetermined narrow band range of wavelengths impinging on said layer.
- 1           3. The structure of Claim 1 wherein said layer comprises a graded-index layer.
- 1           4. The structure of Claim 3 wherein said graded-index layer comprises a plurality of materials deposited on said substrate to a predetermined thickness wherein said layer as deposited has a stoichiometric composition
- 5           which varies in a predetermined pattern as a function of said thickness to produce successive gradations in the index of refraction in said layer in said predetermined pattern.

1           5. The structure of Claim 3 wherein said layer  
comprises a selected plurality of materials deposited  
on said substrate to a thickness having a predetermined  
profile wherein the stoichiometric composition of said  
5 layer as deposited varies in a first predetermined  
pattern as a function of thickness and in a second  
predetermined pattern laterally across said substrate  
to produce successive gradations in said index of  
refraction in said first and second predetermined  
10 patterns as a function of said thickness and as a  
function of the lateral position on said substrate.

1           6. The structure of Claim 1 wherein said substrate  
is formed of plastic material.

1           7. The structure of Claim 6 wherein said plastic  
material is polycarbonate.

1           8. The structure of Claim 1 wherein the asphericity  
of said substrate surface is designed to compensate  
optical aberrations.

1           9. A high efficiency optical combiner comprising:  
a substrate having at least one aspheric surface  
and a second surface;  
a graded-index coating applied to one surface  
5 of said substrate for providing a selectively reflective  
optical function; and  
a broad band antireflective coating applied  
to the other surface of said substrate to minimize  
reflection of incident radiation in the visible wavelength  
10 range,  
said graded-index coating and said anti-  
reflective coating sandwiching said substrate.

1           10. The optical combiner of Claim 9 wherein  
said graded-index layer is of uniform thickness.

1           11. The optical combiner of Claim 9 wherein said  
substrate is formed of plastic material.

1           12. The optical combiner of Claim 9 wherein said  
selectively reflective function comprises the reflectance  
of radiation within one or more predetermined narrow  
band ranges of wavelengths impinging on said coating.

1           13. The optical combiner of Claim 9 wherein said  
graded-index coating comprises a layer of chosen  
materials deposited on said substrate to a predetermined  
thickness wherein said layer as deposited has a  
5 stoichiometric composition which varies as a function  
of said thickness to produce successive gradations in  
the index of refraction in said layer in said pre-  
determined periodic pattern.

1           14. The optical combiner of Claim 13 wherein said  
predetermined periodic pattern is a non-sinusoidal  
pattern.

1           15. The optical combiner of Claim 14 wherein the  
magnitude of the modulation in the index is increased  
to broaden the bandwidth of the peak reflectivity of  
the coating.

1           16. The optical combiner of Claim 13 wherein said  
predetermined periodic pattern comprises a linear  
superpositioning of a plurality of sinusoidal patterns  
selected to produce multiple peaks in the spectral  
5           reflectivity response of said combiner.

1           17. The optical combiner of Claim 14 wherein the  
average index is greater than about 1.54.

1           18. In a display apparatus for combining images,  
an improved optical combiner comprising:

                  a substrate having at least a first surface  
defining an aspheric contour and a second surface;  
5           and

                  a layer formed on one of said surfaces, said  
layer comprising a diffraction-type reflective coating  
for reflecting radiation within one or more predetermined  
narrow band ranges of wavelengths impinging on said  
10          layer.

1           19. The apparatus of Claim 18 wherein the  
asphericity of said first surface is adapted to compensate  
aberrations in said display apparatus.

1           20. The apparatus of Claim 18 wherein said layer  
comprises a graded-index coating.

1           21. The apparatus of Claim 20 wherein said graded-  
index layer comprises a plurality of materials deposited  
on said substrate to a predetermined thickness wherein  
said layer as deposited has a stoichiometric composition  
5 which varies in a predetermined pattern as a function  
of said thickness to produce successive gradations in  
the index of refraction in said layer in said pre-  
determined pattern.

1           22. The apparatus of Claim 21 wherein the  
asphericity of said first surface is adapted to compensate  
aberrations in said display system, said predetermined  
pattern being generally parallel to the surface of said  
5 coating.

1           23. The apparatus of Claim 20 wherein the surface  
of the coating remote from said substrate is exposed to  
the atmosphere.

1           24. The apparatus of Claim 18 wherein said layer  
comprises a selected plurality of materials deposited  
on said substrate to a thickness having a predetermined  
profile wherein the stoichiometric composition of said  
5 layer as deposited varies in a first predetermined  
pattern as a function of thickness and in a second  
predetermined pattern laterally across said substrate  
to produce successive gradations in said index of  
refraction in said first and second predetermined  
10 patterns as a function of said thickness and as a  
function of the lateral position on said substrate.

1           25. The apparatus of Claim 18 wherein said coating  
comprises a graded-index coating applied to one of said  
substrate surfaces and further comprising a broad band  
antireflective coating applied to the other of said  
5       substrate surfaces.

1           26. The apparatus of Claim 18 wherein said  
substrate is formed of plastic material.

1           27. Biocular display apparatus for mounting on a  
helmet to provide biocular images combined with external  
images received through a helmet visor comprising:

5               an object source mounted adjacent the helmet  
for providing a display;

              beam splitting means for splitting incident  
light from the object source into separately directed  
beams;

              a generally transparent visor for mounting on  
10       said helmet having dual optical combiner elements  
oriented at a selected angle, said combiner elements  
comprising a substrate having an aspheric surface and  
a diffraction-type reflecting coating formed thereon  
for reflecting radiation within one or more predetermined  
15       narrow band ranges of wavelengths, said combiner elements  
being substantially transparent to permit the helmet  
wearer to view external scenes therethrough but having  
the capability of reflecting light directed thereto  
from the object source to project biocular images at  
20       respective exit pupils in the general vicinity of the  
helmet wearer's eyes;



means between the object source and the  
splitting means for directing light from the object  
source to the splitting means; and

25 fold means between the splitting means and  
the combiner elements for directing the beams from the  
splitting means toward the respective combiner elements.

1 28. The display apparatus of Claim 27 wherein  
said substrate is formed of plastic material.

1 29. The display apparatus of Claim 28 wherein  
said coating comprises a graded-index layer.

1 30. The display apparatus of Claim 29 wherein  
said graded-index layer comprises a plurality of materials  
deposited on said substrate to a predetermined thickness  
profile wherein said layer as deposited has a  
5 stoichiometric composition which varies in a predetermined  
pattern as a function of said thickness to produce  
successive gradations in the index of refraction in  
said layer in said predetermined pattern.

1 31. The display apparatus of Claim 29 wherein  
said layer comprises a selected plurality of materials  
deposited on said substrate to a thickness having a  
predetermined profile wherein the stoichiometric  
5 composition of said layer as deposited varies in a  
first predetermined pattern as a function of thickness  
and in a second predetermined pattern laterally across  
said substrate to produce successive gradations in  
said index of refraction in said first and second  
10 predetermined patterns as a function of said thickness  
and as a function of the lateral position on said  
substrate.

1           32. The display apparatus of Claim 27 wherein the asphericity of said combiner surface compensates optical aberrations in said display apparatus.

1           33. The display apparatus of Claim 27 wherein the directing means is a relay lens comprising a modified Cooke triplet including aspheric lens surfaces and a further lens element including aspheric surfaces.

1           34. The display apparatus of Claim 33 wherein the relay lens is off-axis.

1           35. The display apparatus of Claim 27 wherein the object source is tilted with respect to the directing means.

1           36. The display apparatus of Claim 27 wherein the directing means comprises a folding prism having an entrance face orthogonal to an optical axis of the apparatus and an exit face at a wedge angle to said axis.

1           37. The display apparatus of Claim 27 wherein the beam splitting means has concave exit surfaces.

1           38. In a head-up display comprising an image  
source, and an optical combiner interposed between a  
user and the external scenery for selectively reflecting  
light from the image source to the user, an improved  
5 optical combiner comprising:

          a substrate having at least one aspheric  
surface; and

          a layer formed on said substrate, said layer  
comprising a diffraction-type reflective coating for  
10 reflecting radiation within one or more predetermined  
narrow band ranges of wavelength impinging on said  
layer.

1           39. The apparatus of Claim 38 wherein said coating  
comprises a graded-index coating.

1           40. The apparatus of Claim 39 wherein said graded-  
index layer comprises a plurality of materials deposited  
on said substrate to a predetermined thickness profile  
wherein said layer as deposited has a stoichiometric  
5 composition which varies in a predetermined pattern as  
a function of said thickness to produce successive  
gradations in the index of refraction in said layer in  
said predetermined pattern.

1           41. The apparatus of Claim 38 wherein said layer  
comprises a selected plurality of materials deposited  
on said substrate to a thickness having a predetermined  
5           profile wherein the stoichiometric composition of said  
layer as deposited varies in a first predetermined  
pattern as a function of thickness and in a second  
predetermined pattern laterally across said substrate  
to produce successive gradations in said index of  
10          refraction in said first and second predetermined  
patterns as a function of said thickness and as a  
function of the lateral position on said substrate.

1           42. The apparatus of Claim 38 wherein the  
asphericity of said combiner surface compensates optical  
aberrations in said display apparatus.

Fig. 1.

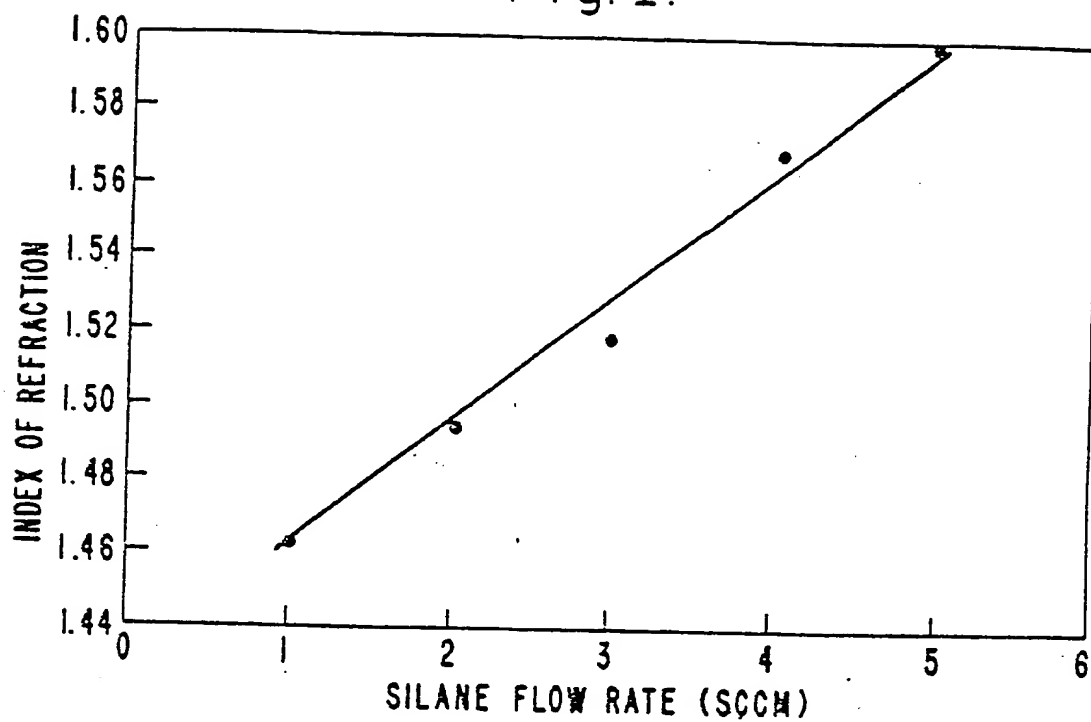
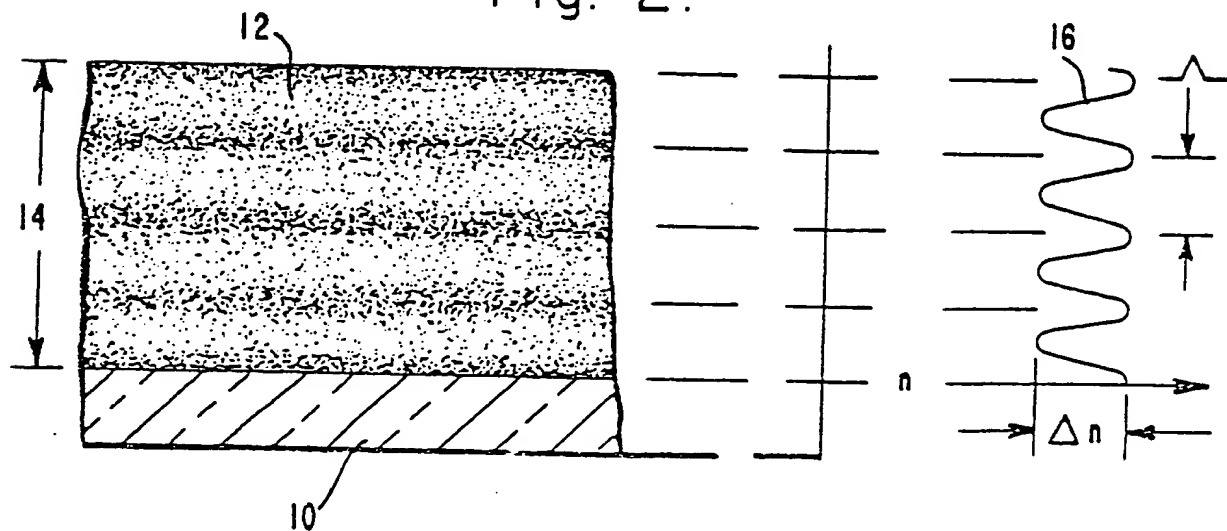


Fig. 2.



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Fig. 3.

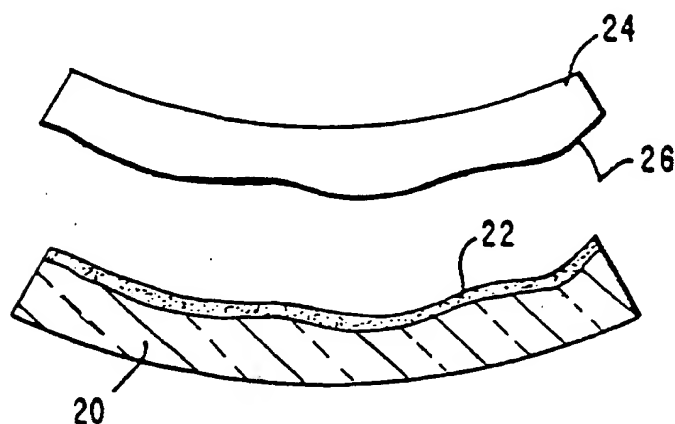
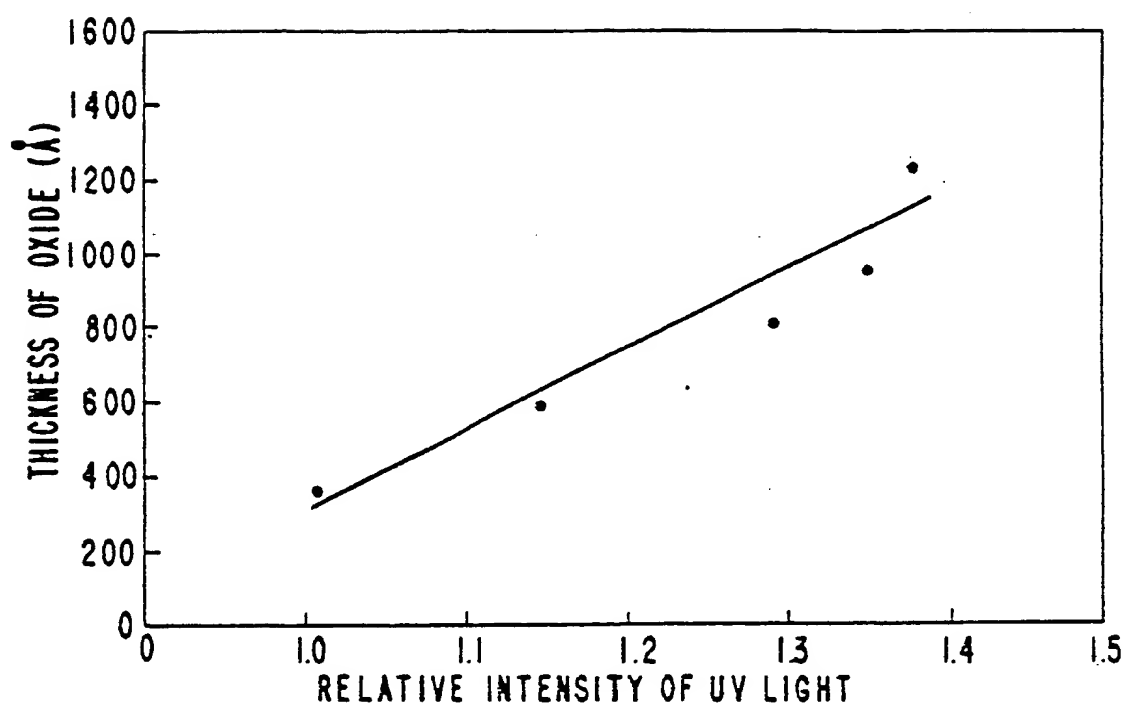


Fig. 4a.

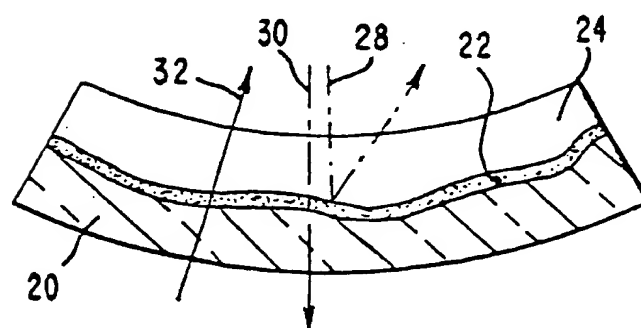


Fig. 4b.

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Fig. 5.

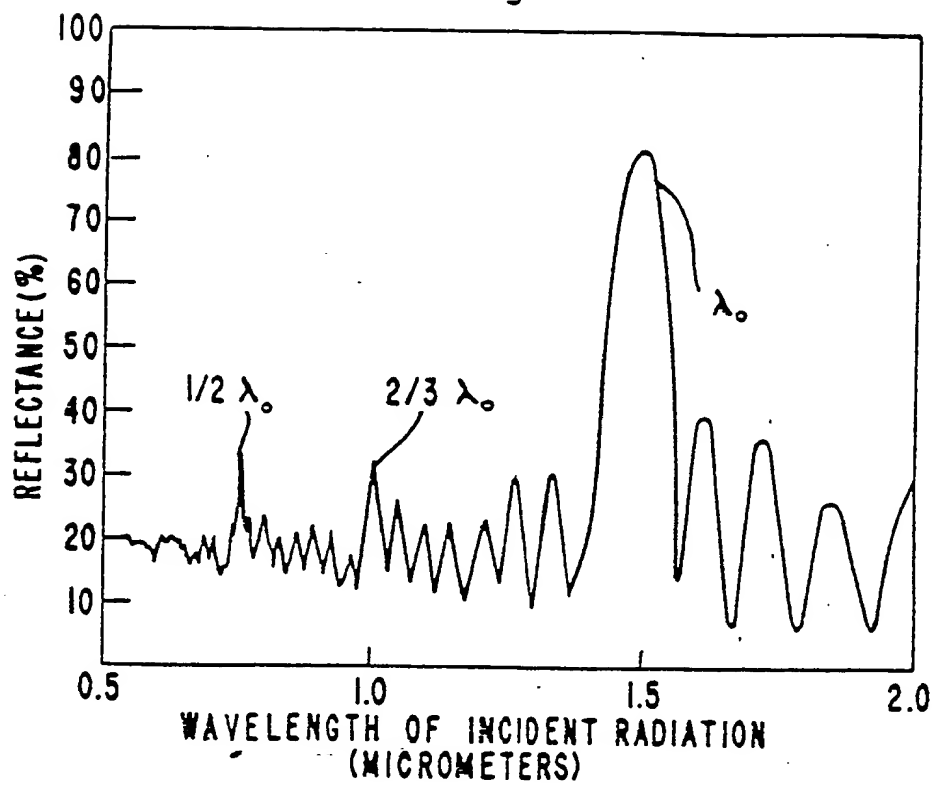
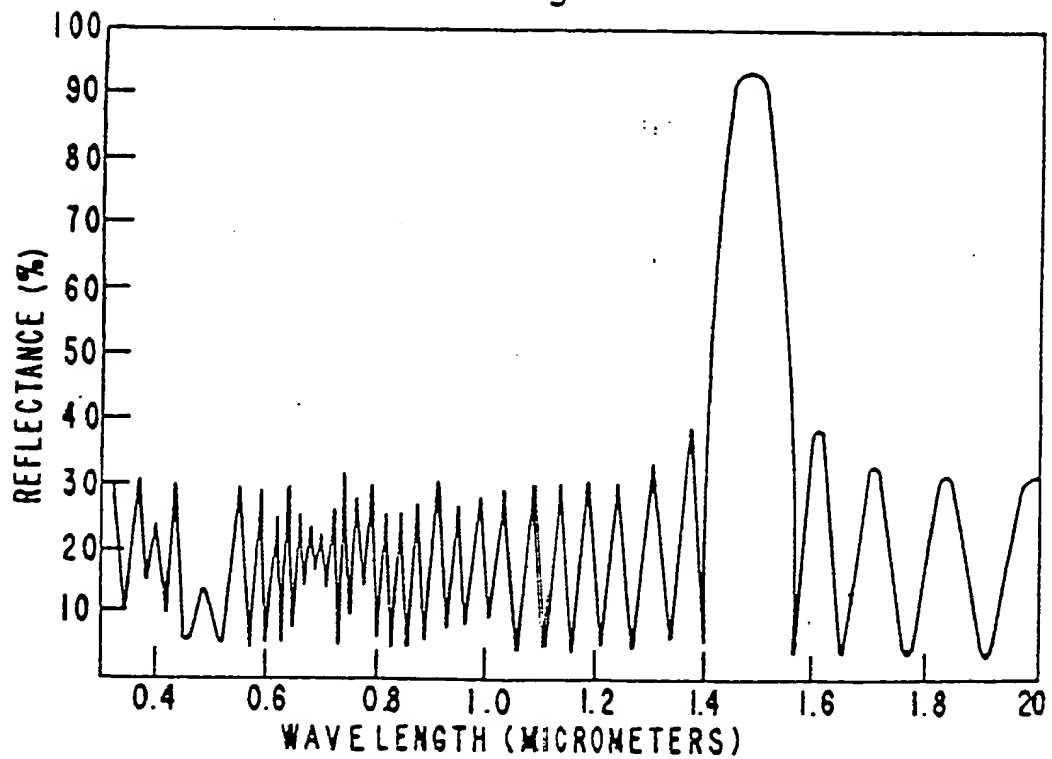


Fig. 6.



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Fig. 7.

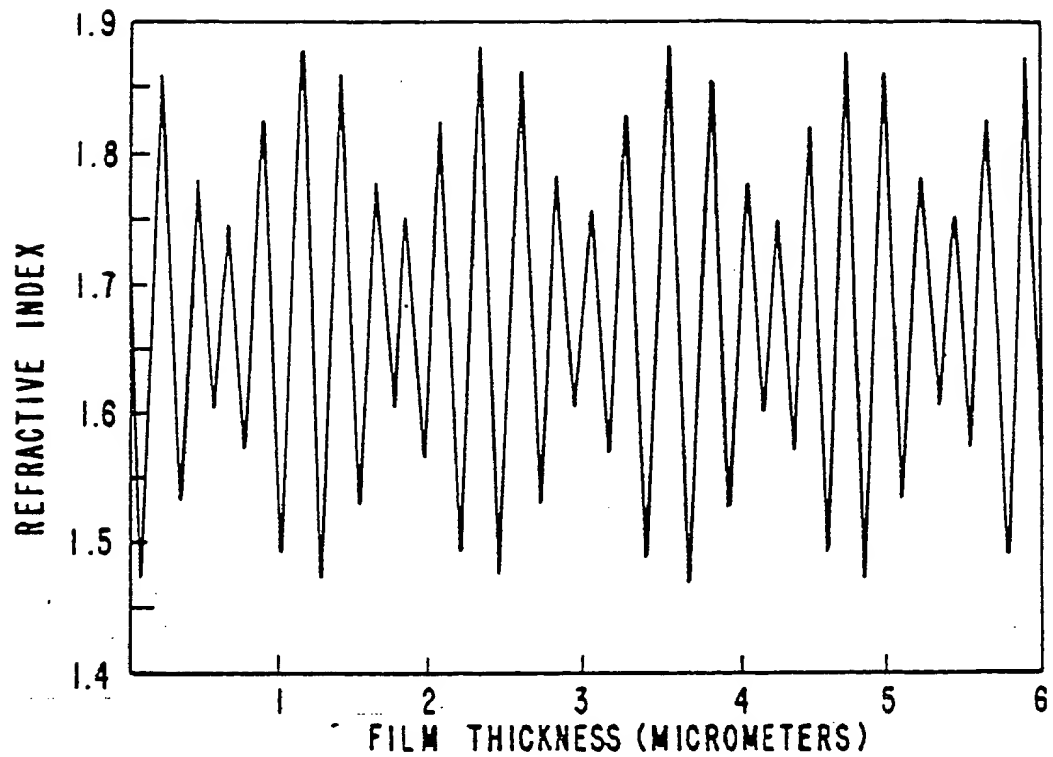
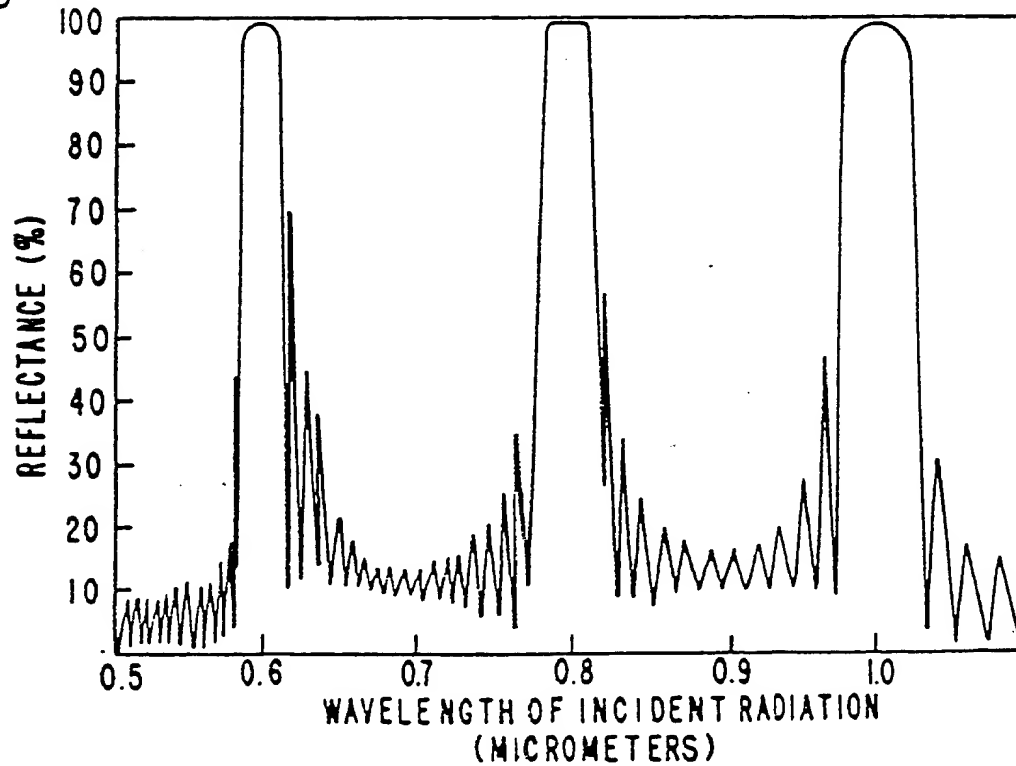


Fig. 8.





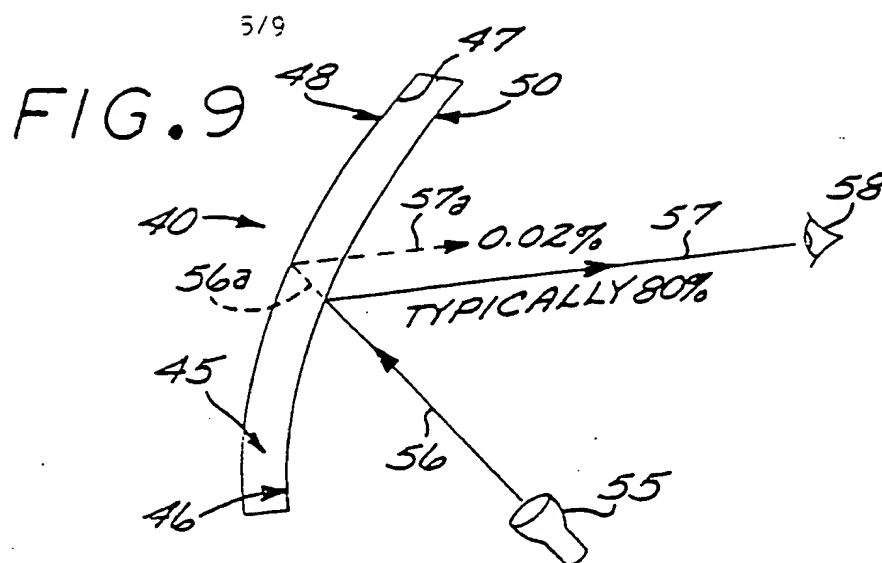


FIG. 10

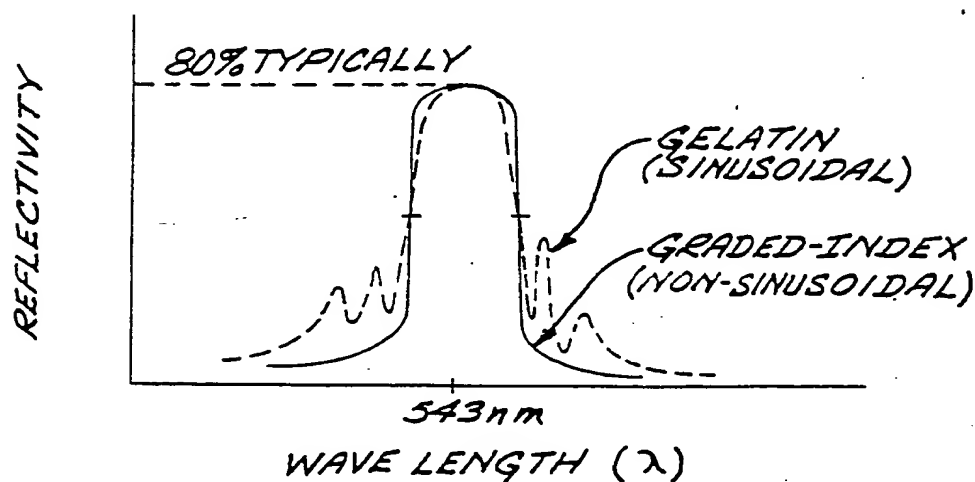
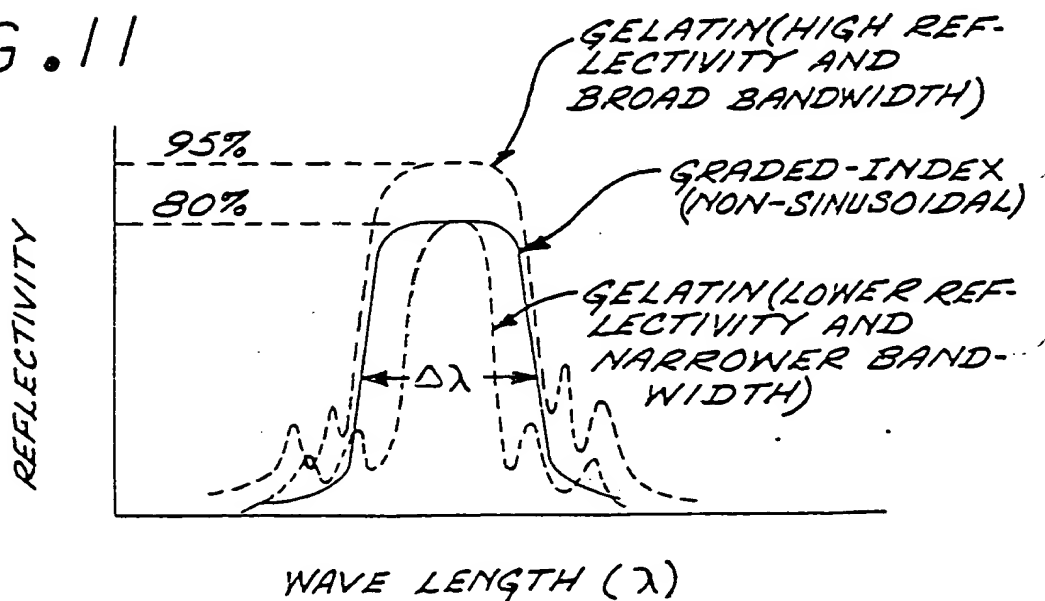


FIG. 11



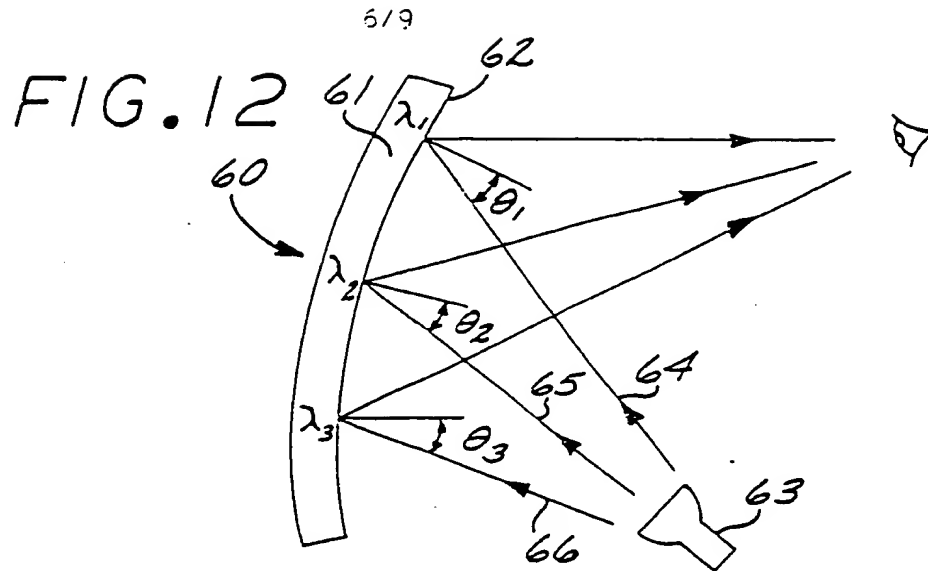


FIG. 13

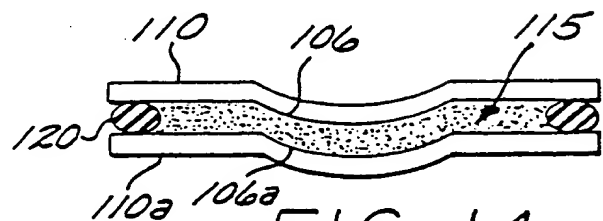
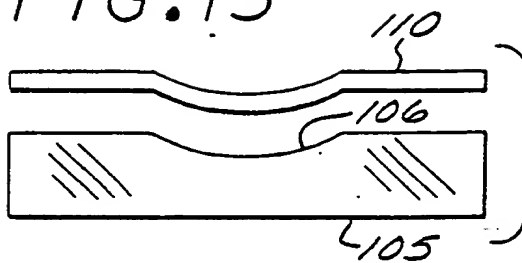
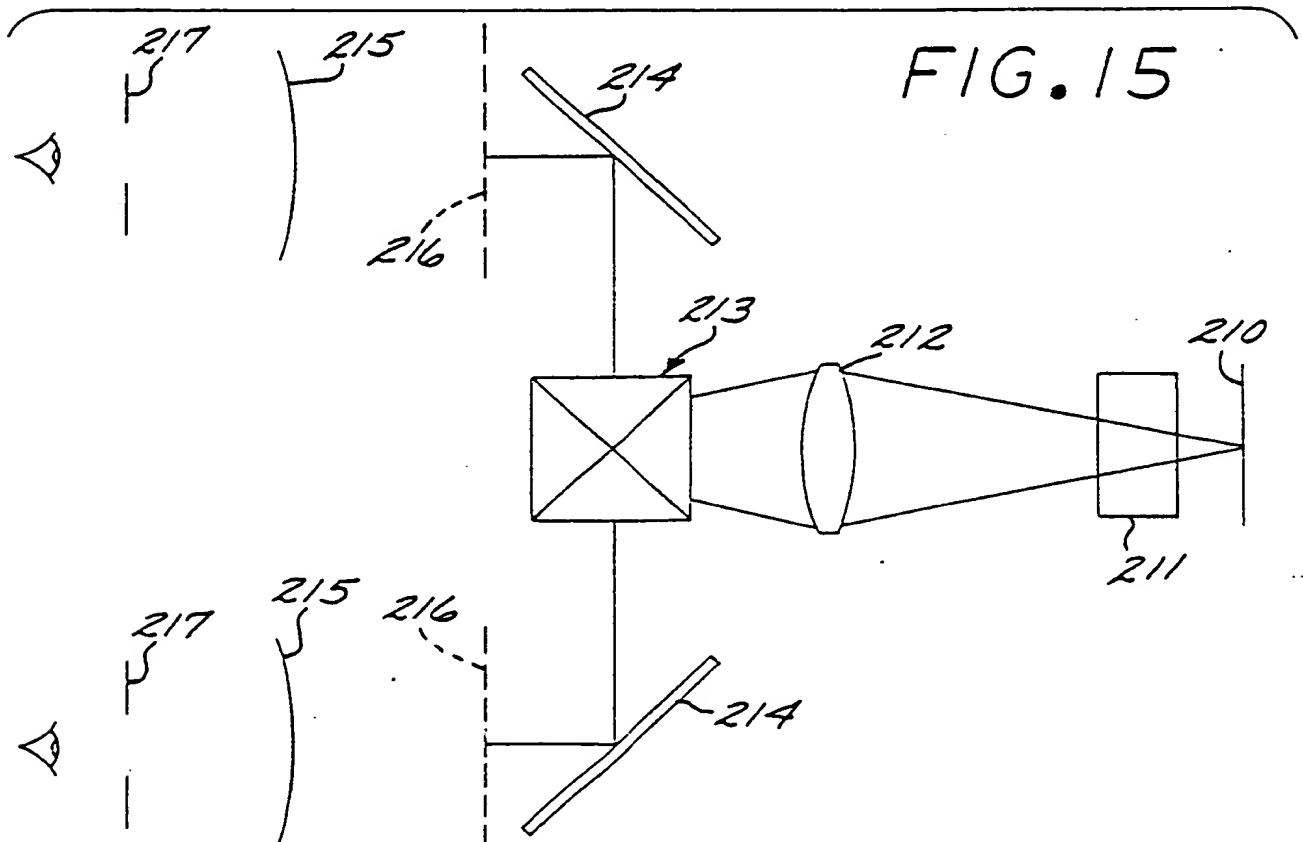


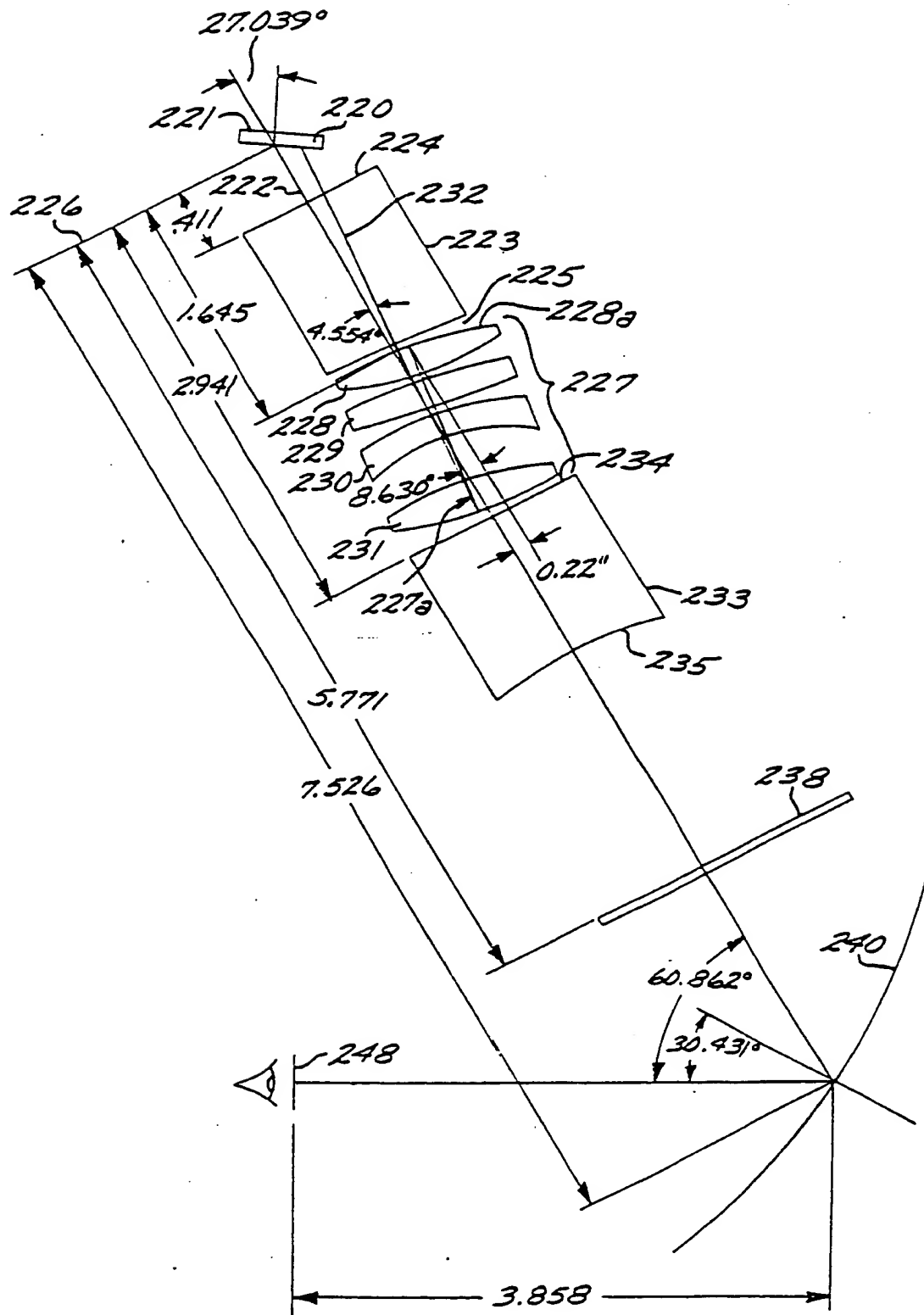
FIG. 14



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FIG. 16



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FIG. 17

